Recent Status of Beam Cooling at S-LSR

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at
COOL11
Alushta, Ukraine
12, September, 2011

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1. Accelerator Facility at ICR, Kyoto University

7 MeV proton Linac (RFQ+ DTL:433 MHz)
100 MeV Electron Linac (S-band, 2857 MHz)
→Calibration of neutrino detectors for T2K experiment
Electron Storage Ring, KSR(100 ~ 300 MeV)→SCRIT
Ion Storage and Cooler ring, S-LSR

2. Beam Cooling at S-LSR

a) Electron Beam Cooling

- Efficient Cooling of Hot Ion Beam by Relative Velocity Sweep
- One dimensional Ordering of proton beam
- Creation of short bunch beam (~3 nsec.)→Bio-medical Beam Irradiation Course with a Vertical Bend

b) Laser Cooling: 40 keV $^{24}Mg^{+}$ Ion Beam

- Longitudinal Cooling of Coasting Beam→3.6 K (limited by IBS)
- Longitudinal Cooling of Bunched Beam→15 K→optimization
- Horizontal Laser Cooling by "Synchro-betatron Coupling Resonance".

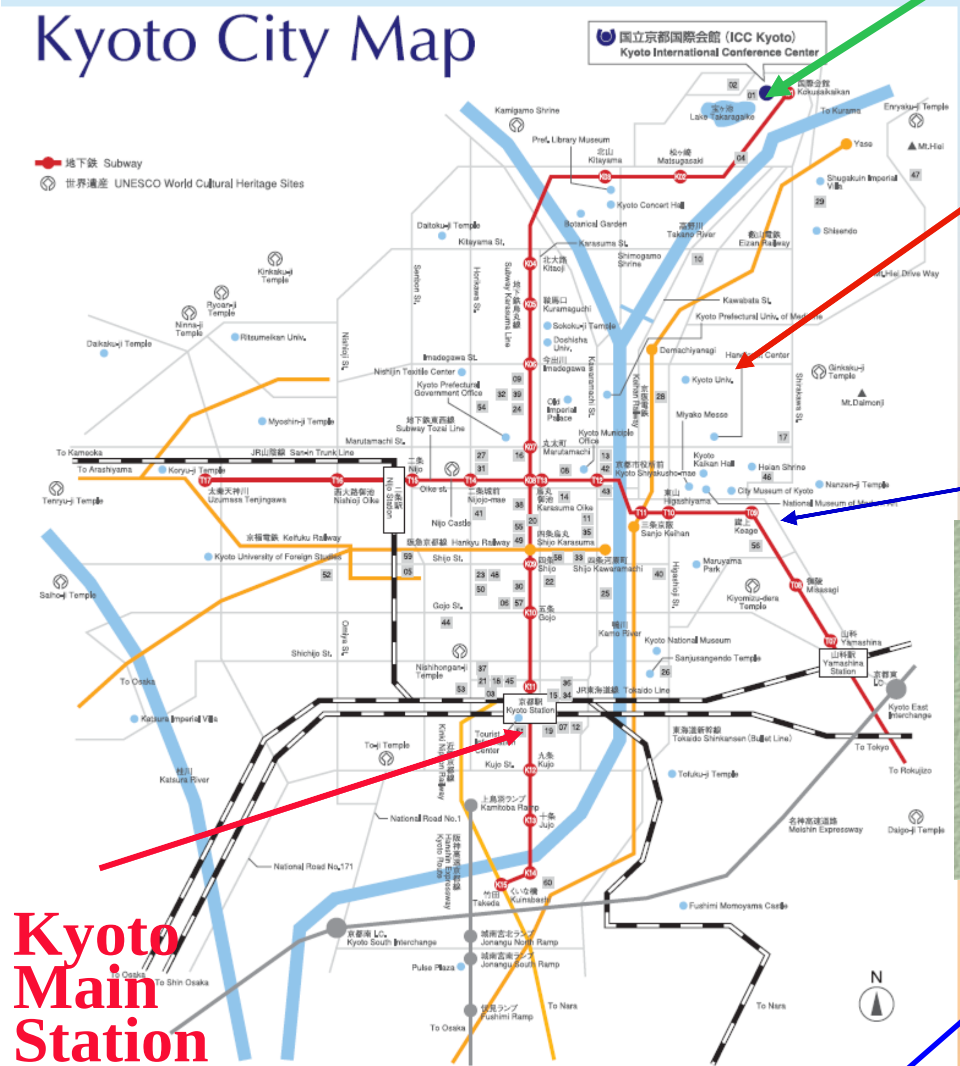
3. Perspective for Future Research→Toward Crystaline Beam

- Further Optimization of Longitudinal laser cooling→Sweep of detuning
- Study of capability of pre-cooling of 40 keV $^{24}Mg^{+-}$

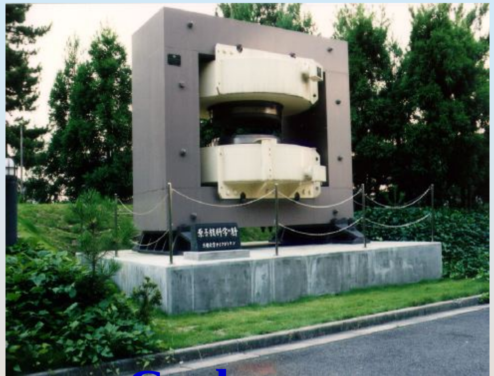
1. Introduction of Our Accelerator Facility

Campus of Kyoto University

Kyoto International Conference Center
23-28, May, 2010, (IPAC'10)



Main Campus



Cyclotron
(1955~1985)

Accelerator Building

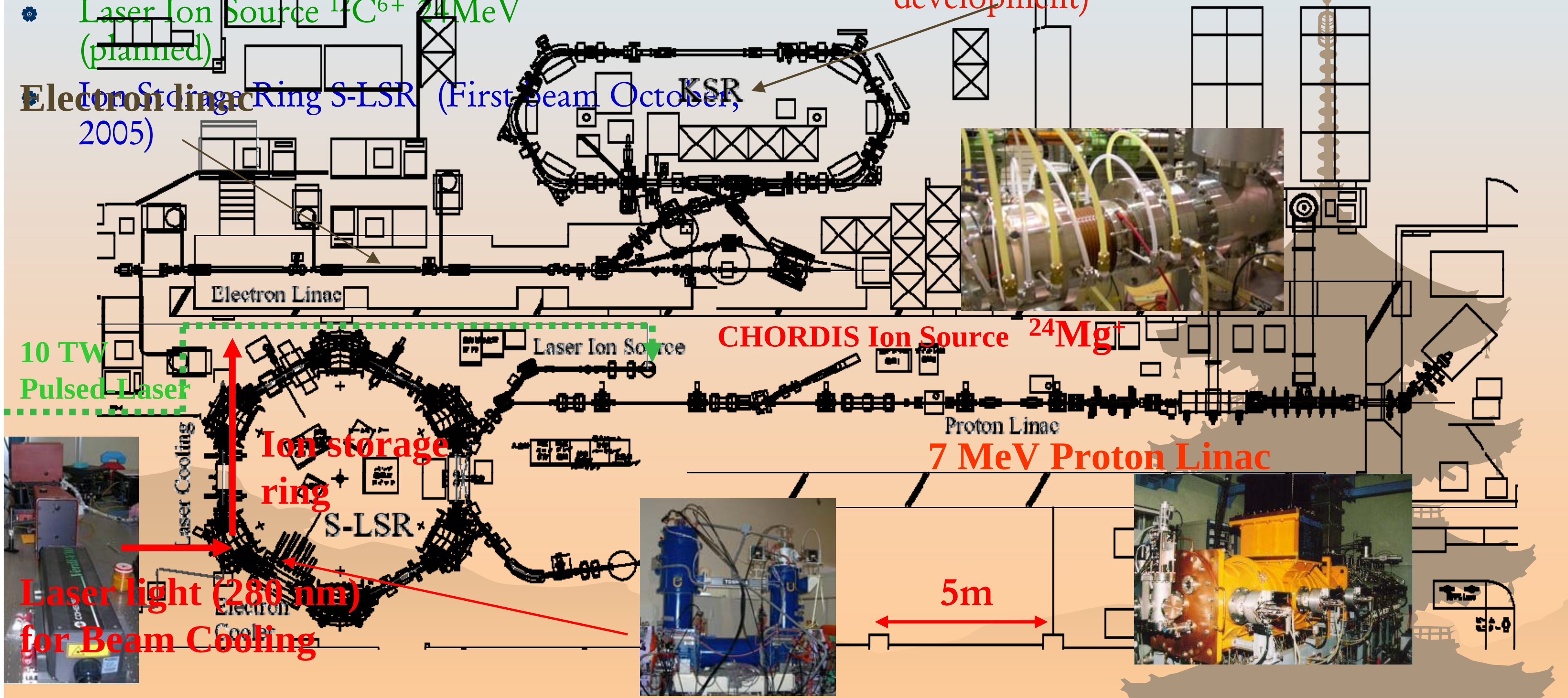
Uji Campus

Kyoto
Main
Station

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 40 keV (existing)
- Laser Cooling for $^{24}Mg^{+}$ (existing- still under development)



Electron Facility

1. **100 MeV Electron Linac**

   Calibration of neutrino detectors for T2K (Tokai to Kamiokande) Experiments at J-PARC.

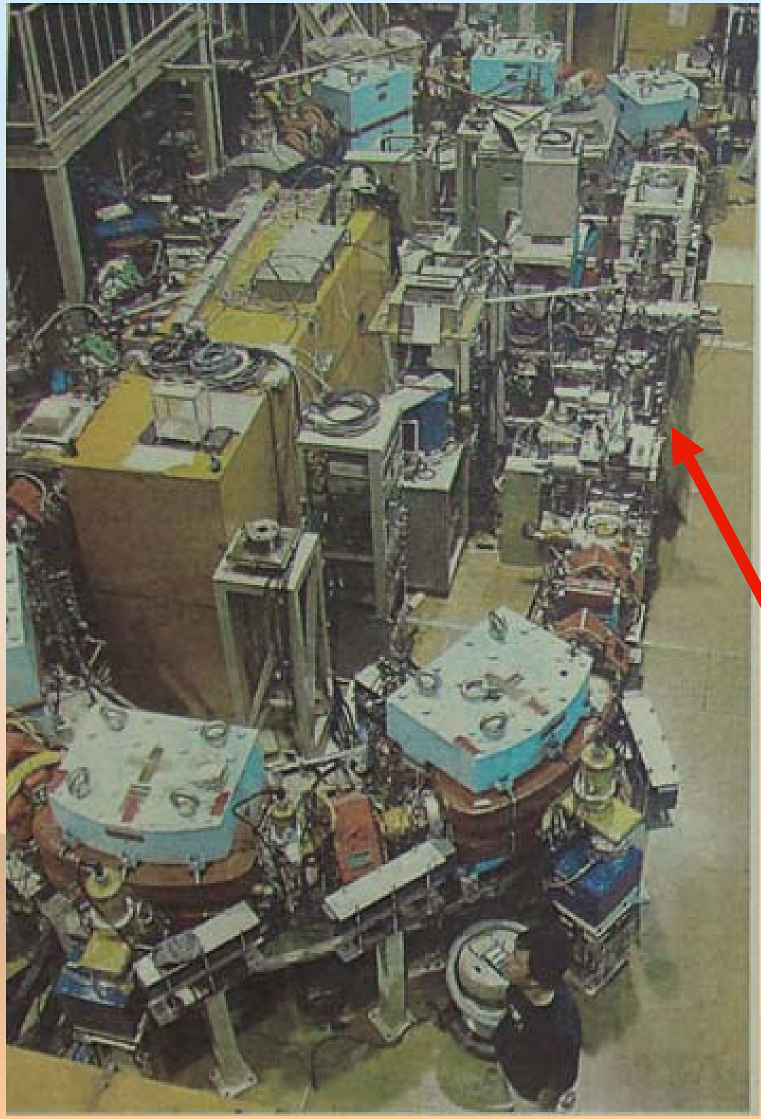
2. **Proof of principle experiment for SCRIT (self-confining radio active isotope ion target) with use of KSR and ion trap of stable nuclei (Cs).**

   7×10^6 Cs Ions Trapped → **Luminosity of 2.5×10^{25} $cm^{-2}s^{-1}$**

   80 mA circulating electron

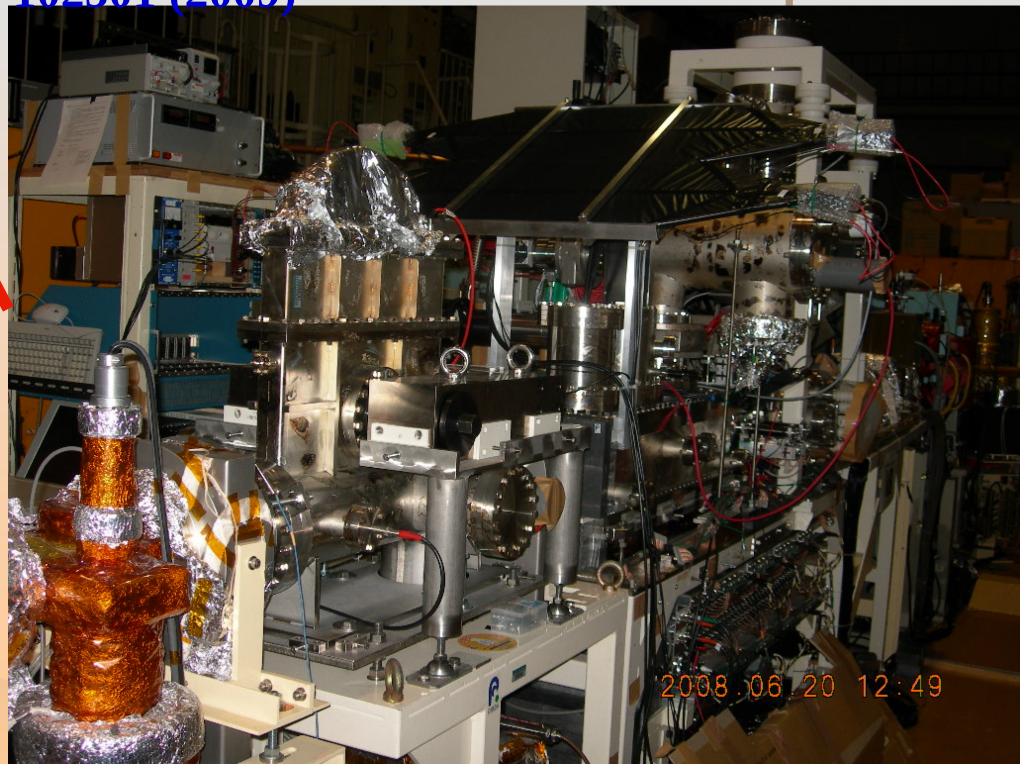
   →Moved to RIKEN

SCRIT Installed into KSR



SCRIT(self-confining radio active isotope ion target)
An "ion trapping" phenomenon in the electron storage ring was successfully utilized for the first time to form the target for electron scattering.

M. Wakasugi et al., Phys. Rev. Lett. 100, 164801 (2008)
T. Suda et al., Phys. Rev. Lett. 102 102501 (2009)

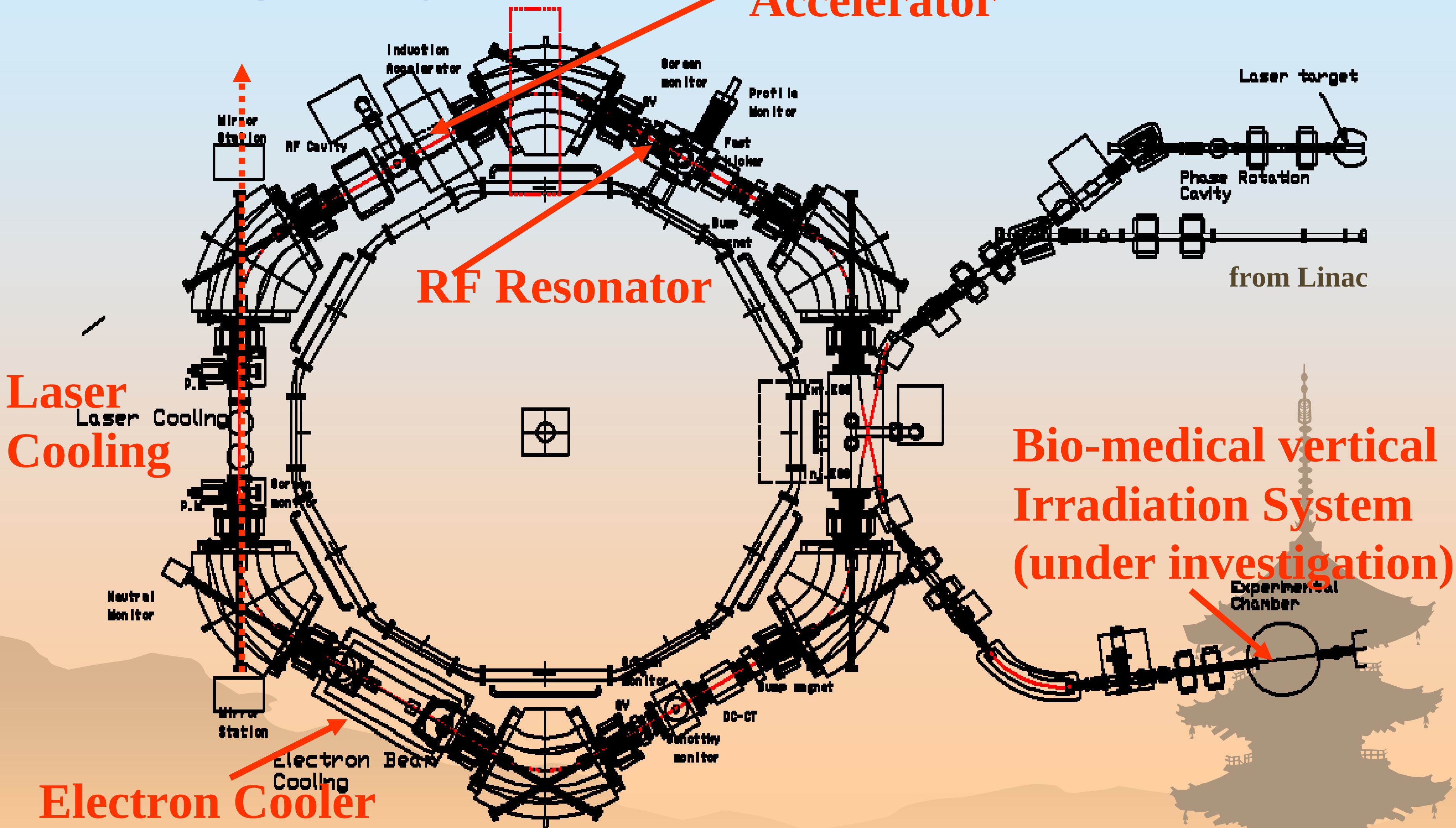


2. Present Status of Beam Cooling at S-LSR

- **Compact Cooler Ring S-LSR**
  - **Circumference 22.56m**
  - **Straight Section Length 1.86m**
- **Electron-Cooling**
  - **Protons 7MeV (Ee=3.8keV)**
    - **Hot proton beam**
    - **Approach to 1D-Ordering**
    - **Short Bunch Formation**
- **Laser Cooling**
  - **$^{24}Mg^{+}$ 40 keV (λ=282 nm)**
  - **Transverse Laser Cooling by "Synchro-Betatron Coupling"**

In operation since October, 2005

Ring Layout


Induction Accelerator
RF Resonator
Laser Cooling
Electron Cooler
Bio-medical vertical Irradiation System (under investigation)
from Linac
Induction Accelerator
Screen monitor
Profile Monitor
Laser target
Phase Rotation Cavity
Mirror Station
RF Cavity
Fast Kicker
Bump magnet
Laser Cooling
Screen monitor
Neutral Monitor
Mirror Station
Electron Beam Cooling
Screen monitor
Bump magnet
DC-CT
Schottky monitor
Experimental Chamber

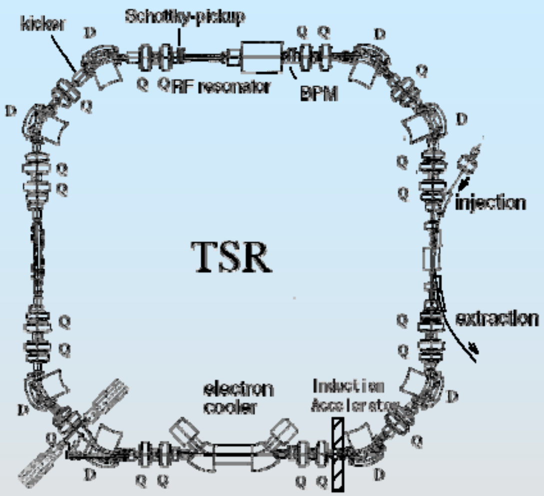
Main Parameters of S-LSR

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)	**1.645 (H), 1.206 (V) :EC, LC(‖)**
	2.068 (H), 1.105 (V) :LC(⊥&‖)
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**

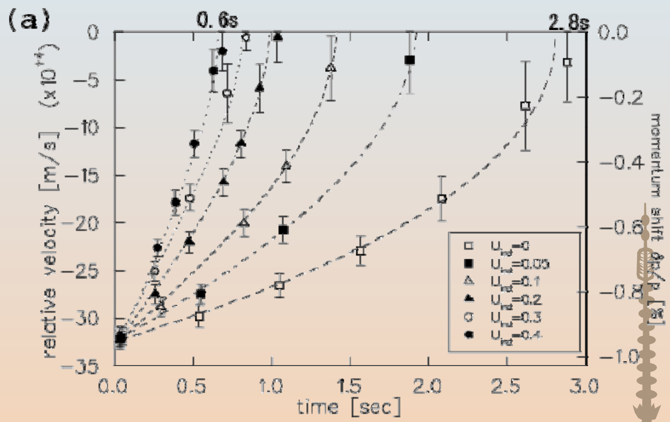
Electron Beam Cooling of Hot Ion Beam

Electron Cooling of Hot Carbon Beam at TSR

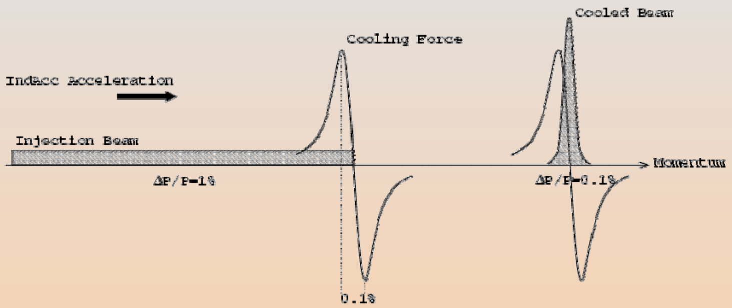
by H. Fadil

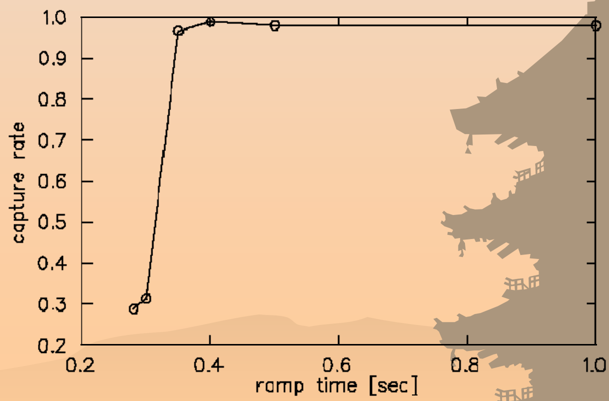


TSR Experiment parameters	
Ion species	C^{6+} 73.3 [MeV]
Electron density	2.4×10^{7} [cm^{-3}]
cooler length	1.2 [m]
Magnetic field	300 [G]
Induction voltage	0 ~ 0.4 [V]

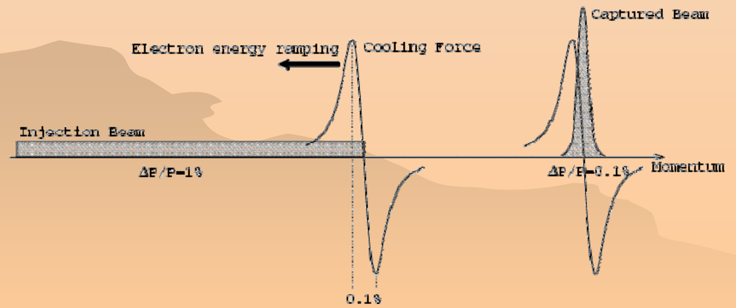


Ion beam energy sweeping scheme

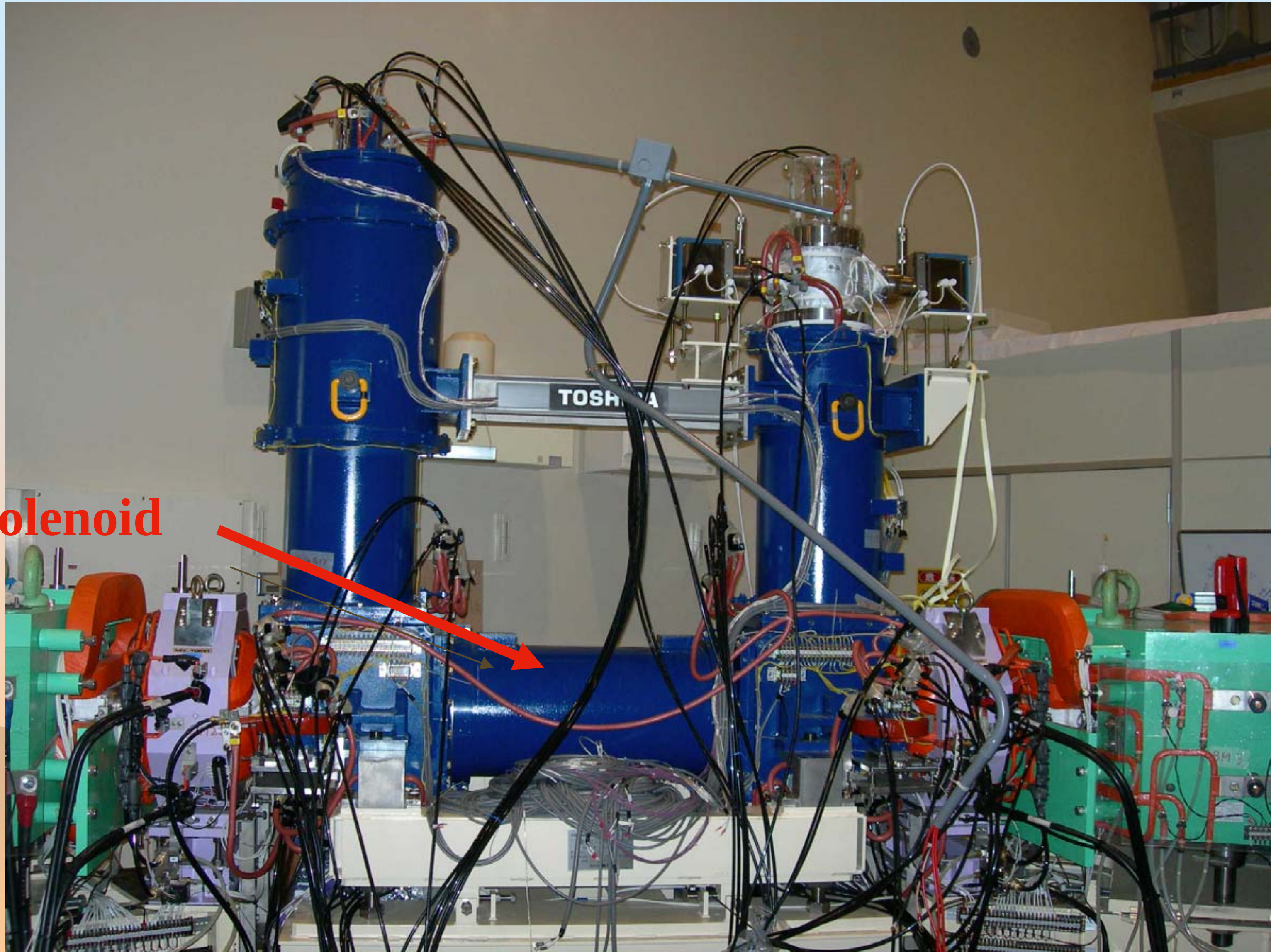




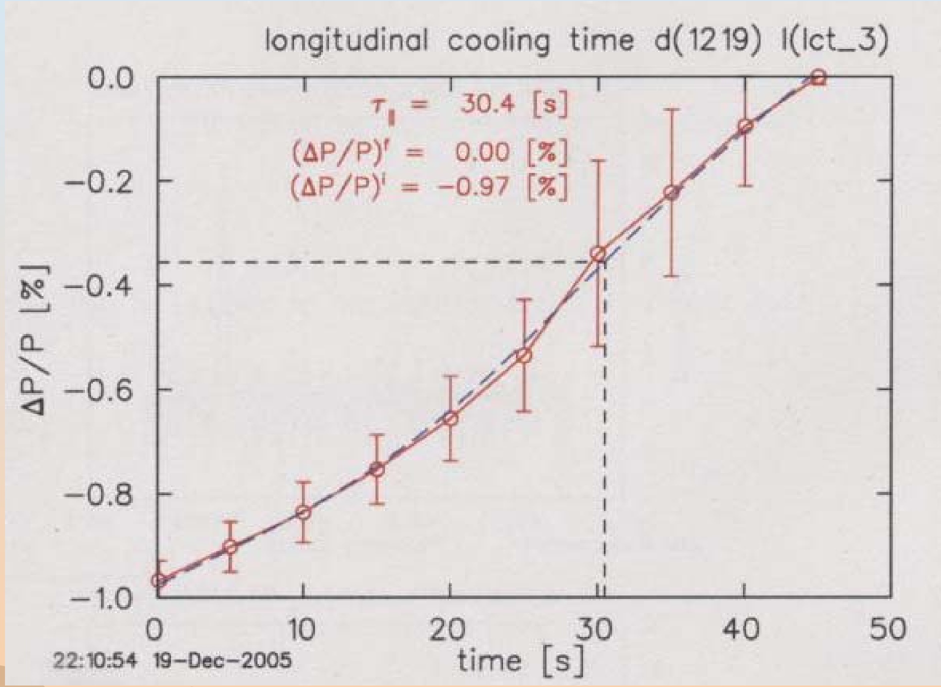
Electron beam energy sweeping scheme



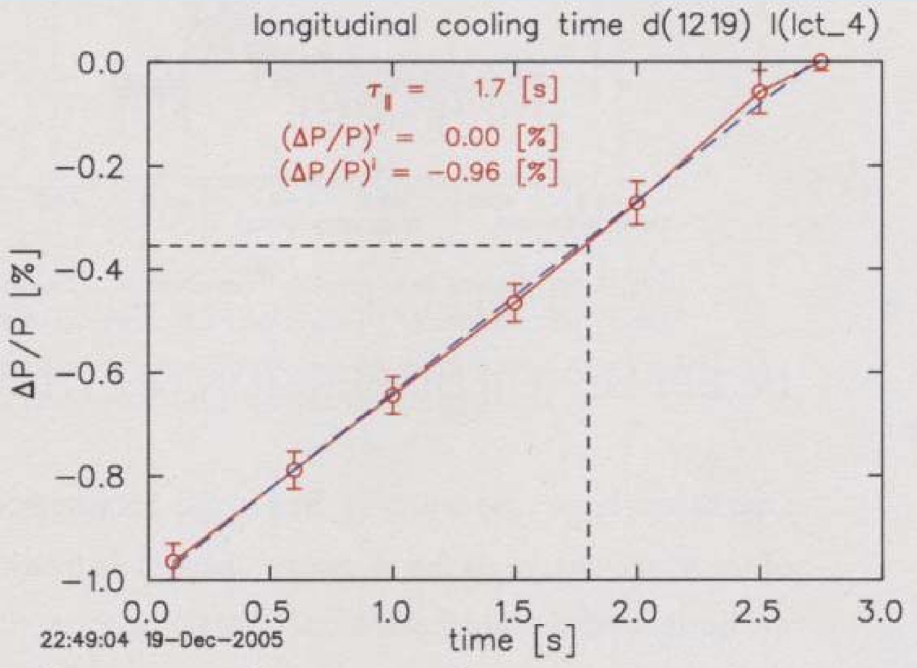
Electron Cooler installed in S-LSR



Electron Cooling of Hot Proton Beam at S-LSR



Withour relative velocity sweep



With relative velocity sweep

1D Ordering of 7 MeV Proton by Electron Cooling

ESR at GSI, by M. Steck

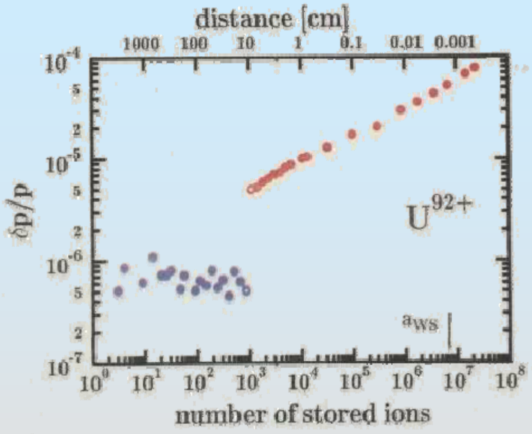


Figure 2. Experimental momentum spreads from Schottky signals vs. number of stored ions in the ESR for electron cooled U^{92+} ions at 240 MeV/u. a_{WS} indicates the Wigner-Seitz radius of eq.(3). (after ref. [9])

CRYRING at Stockholm, by H. Danared

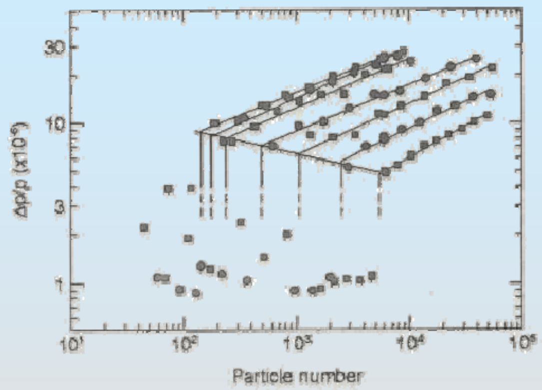


Fig. 5: Relative momentum spread as a function of particle number for the lowest seven electron densities represented in Fig. 2. The density increases from the upper left to the lower right. For each density, a line is fitted to the data points. A line is also drawn through the points corresponding to 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

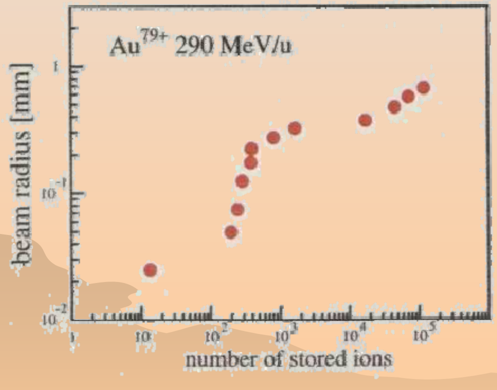


Figure 3. Beam radius measured with a beam scraper vs. number of stored ions in the ESR for electron cooled Au^{79+} ions at 290 MeV/u (from ref. [10]).

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

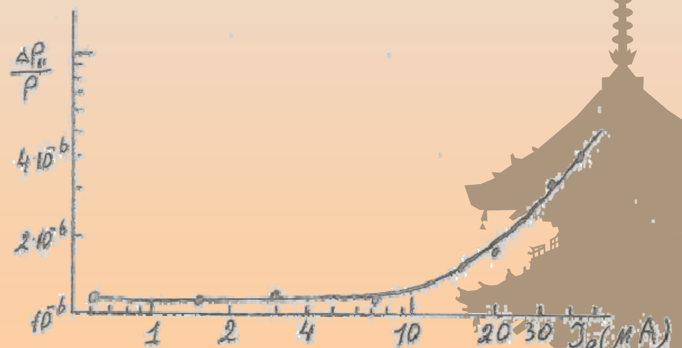
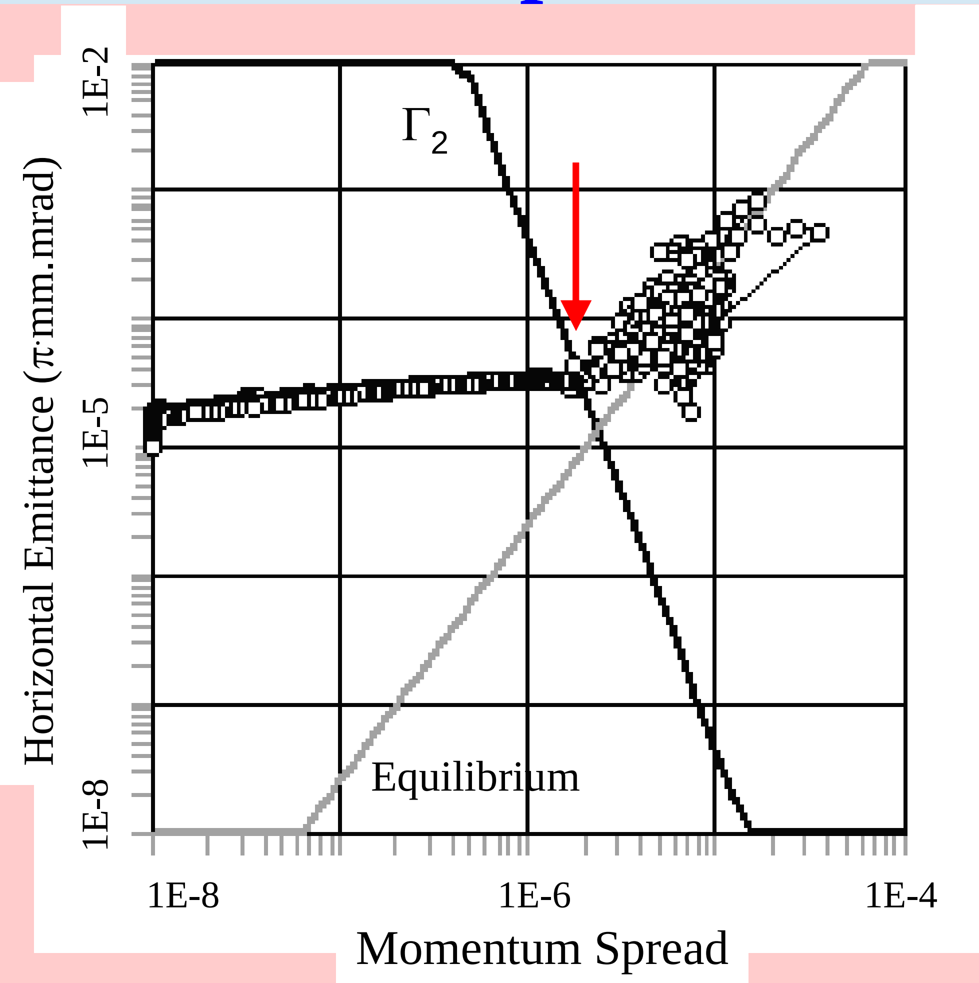


Fig. 6. The momentum spread of proton beam versus current J_p.

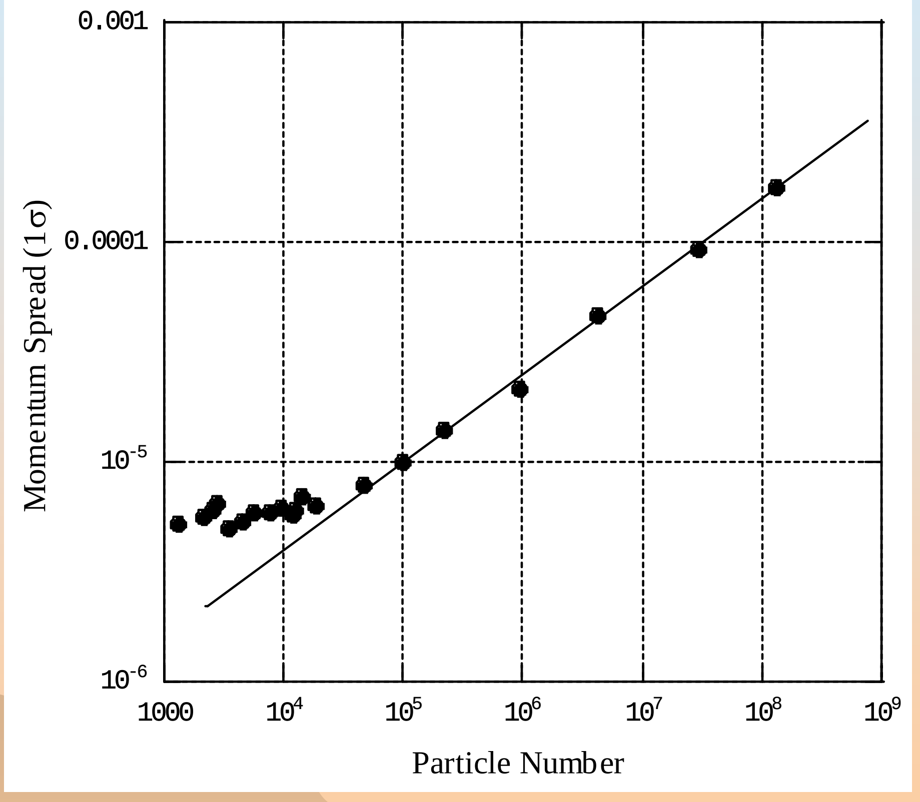
Simulation with Betacool predicts 1D ordering of 7 MeV proton at S-LSR -particle number of 3000-



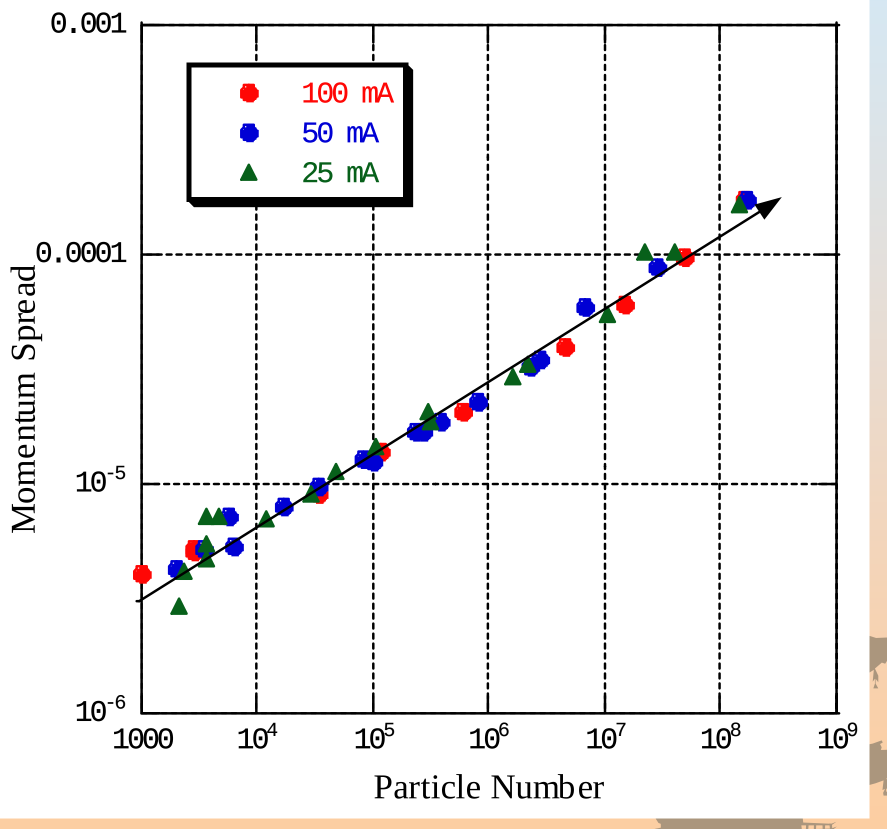
$$\Gamma_2 \equiv \frac{Z^2 e^2}{4\pi\epsilon_0 \sigma_\perp k_B T_\parallel}$$

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

Fractional Momentum Spread vs Particle Number

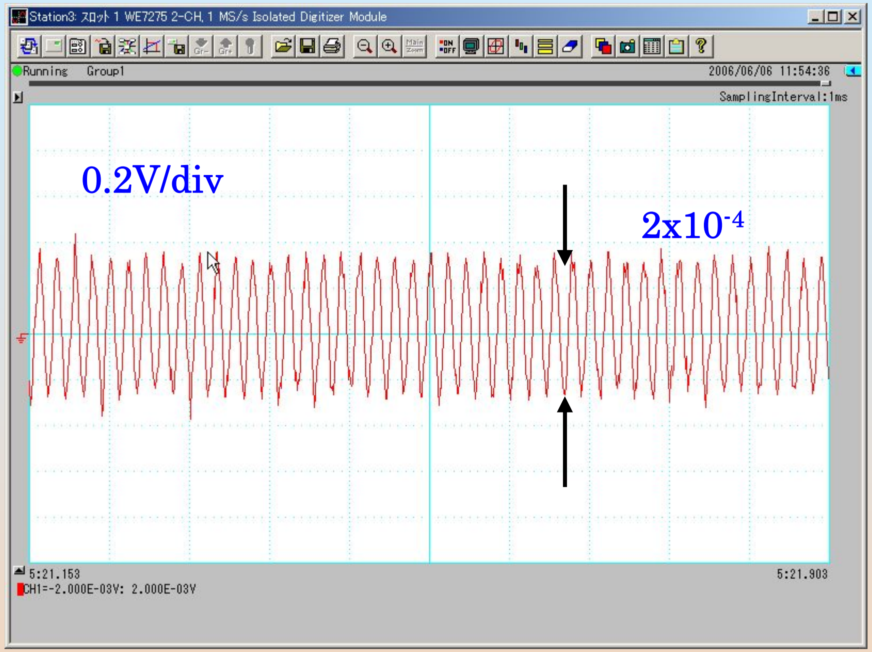


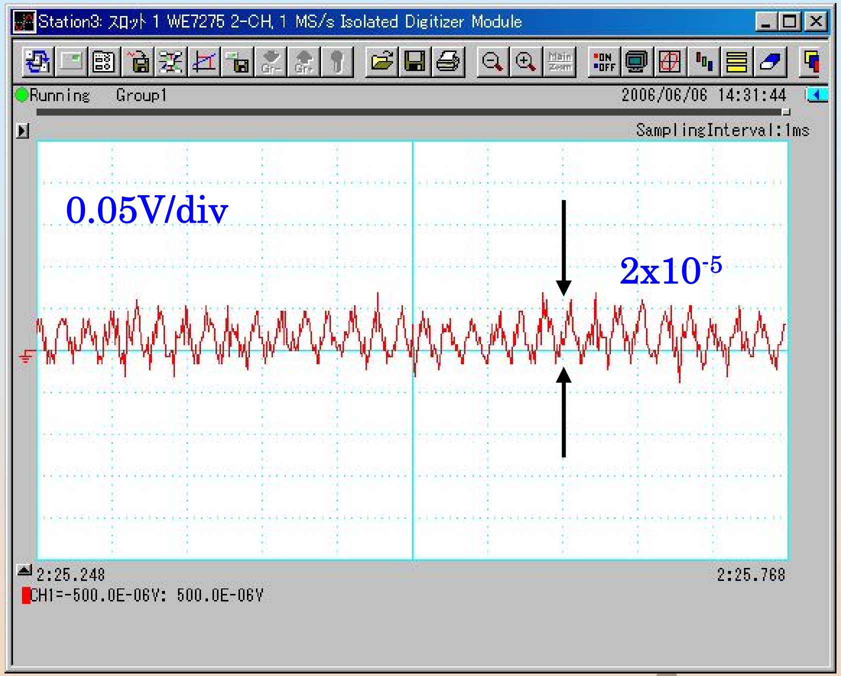
Data in Feb., 2006

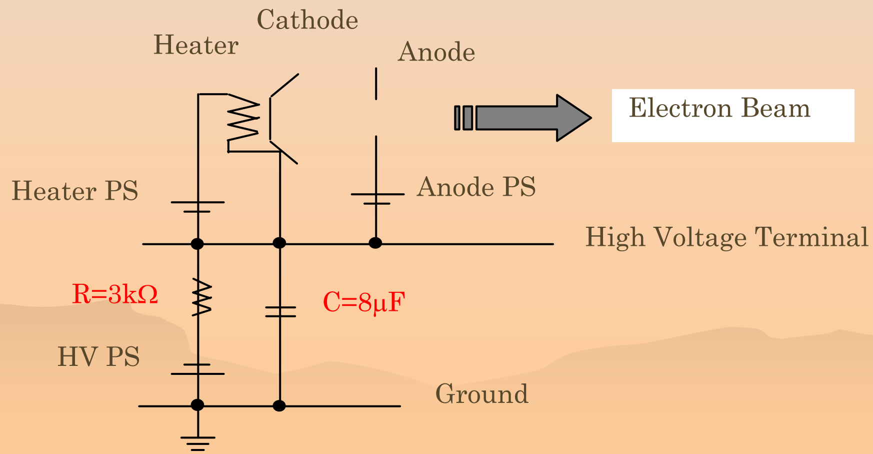


Data on the 8th, June, 2006

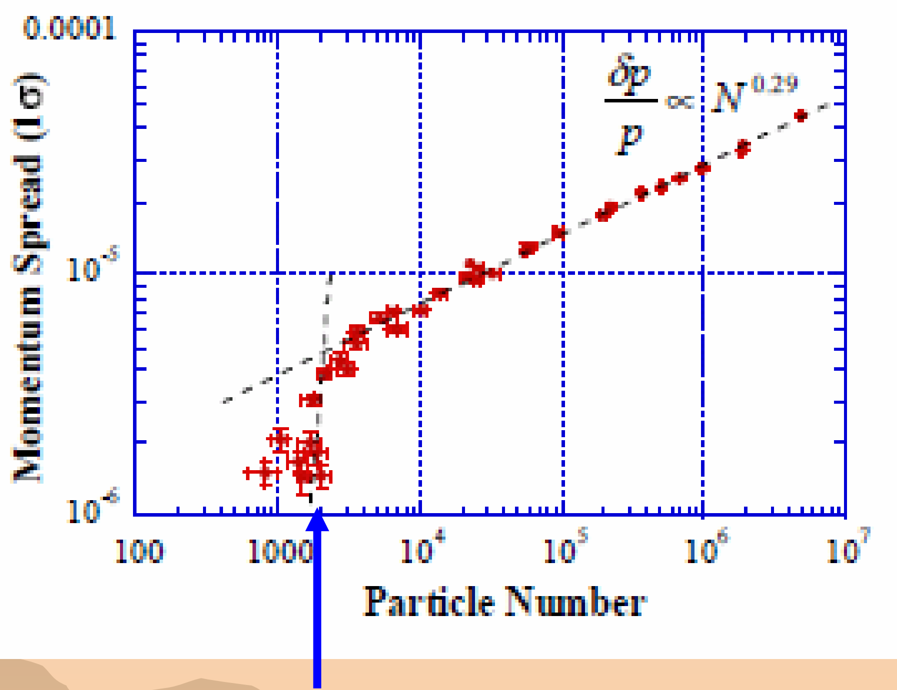
Reduction of Ripple in Electron Gun

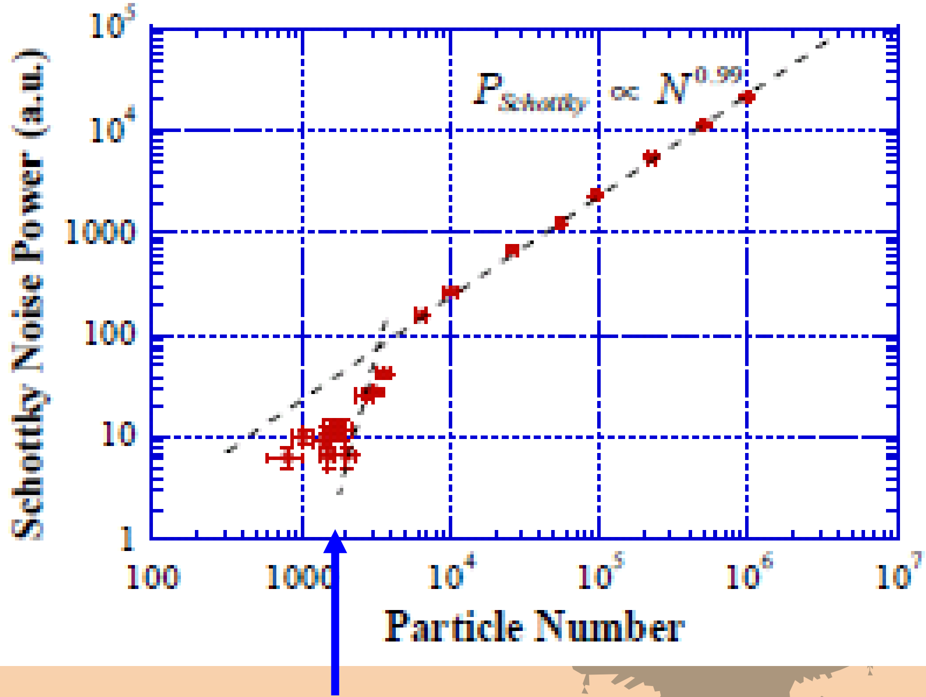






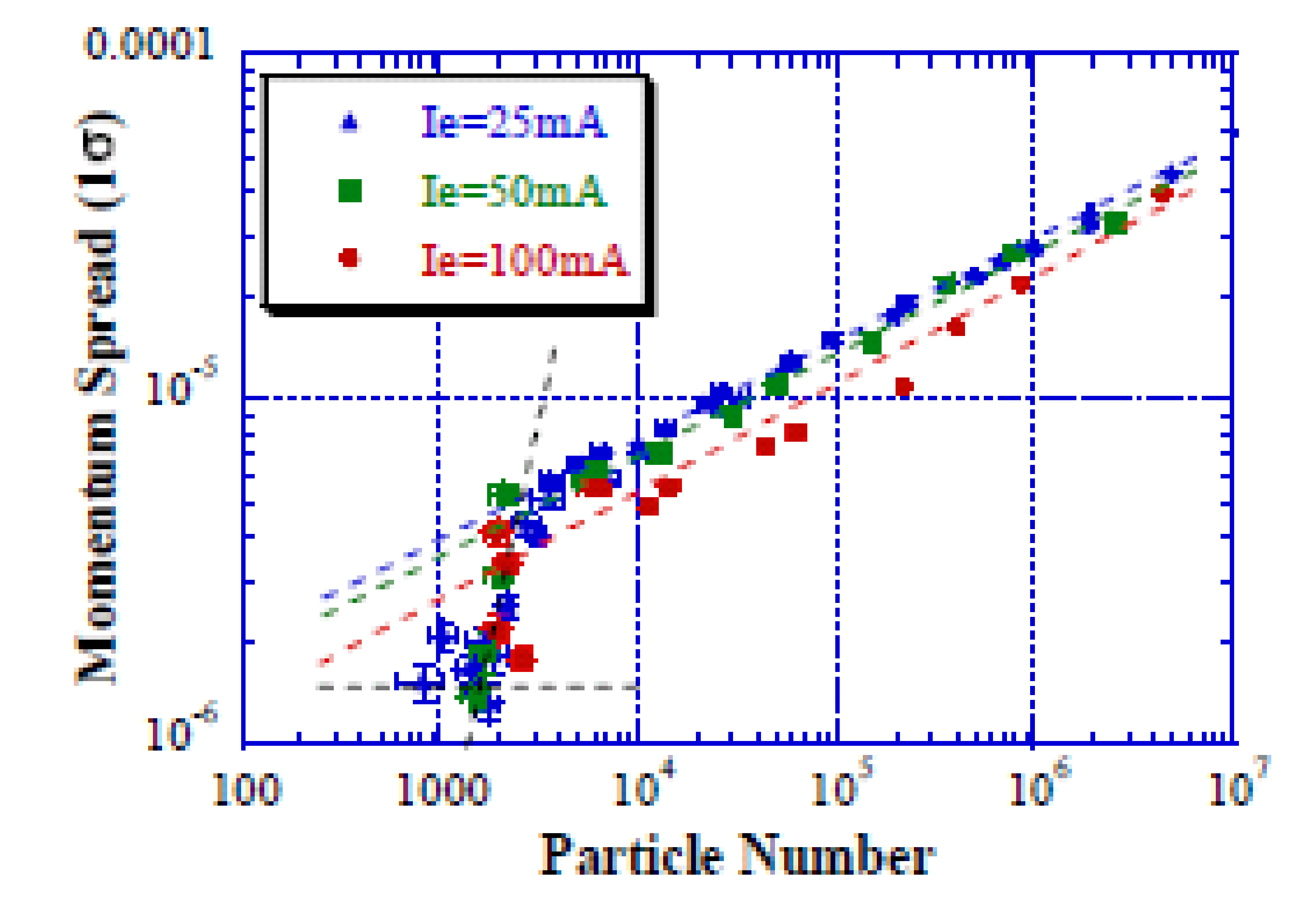
Abrupt Jump of Momentum Spread and Schottky Power





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

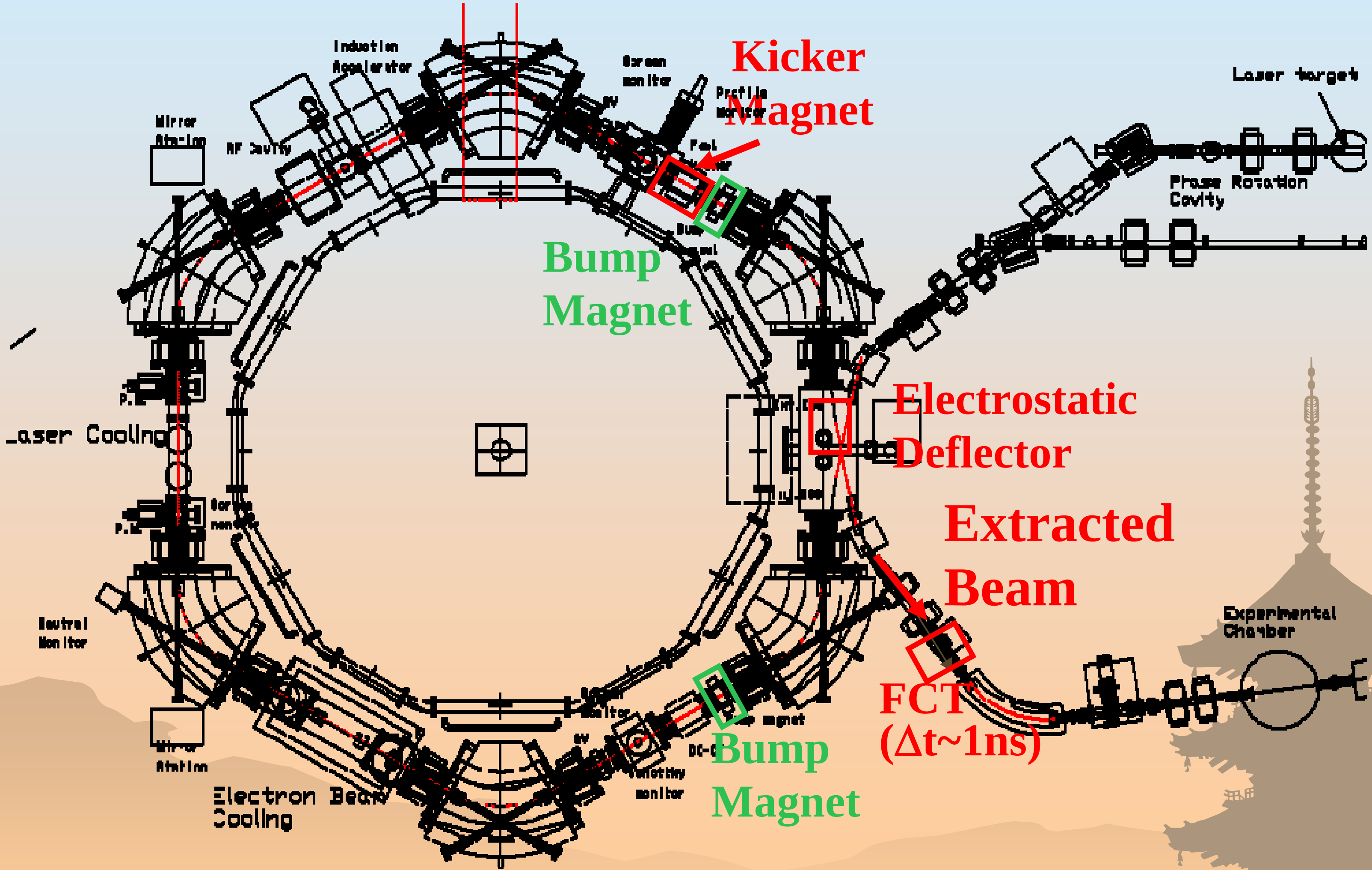
Phase Transition to 1D Ordered State



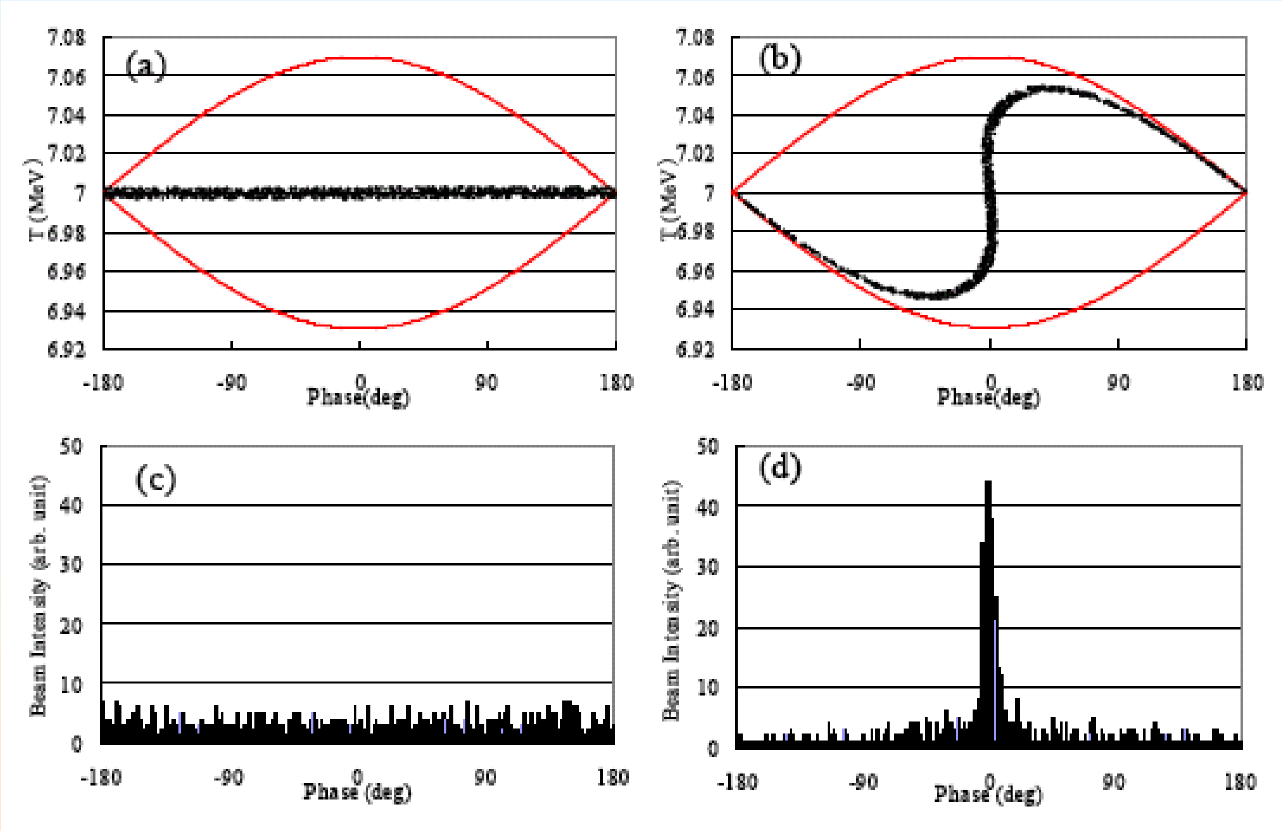
T. Shirai et al., PRL, 98 (2007) 204801

Creation of Ultra-short Bunch Beam and its fast extraction →Verical Irradiation System

Fast Extraction System at S-LSR

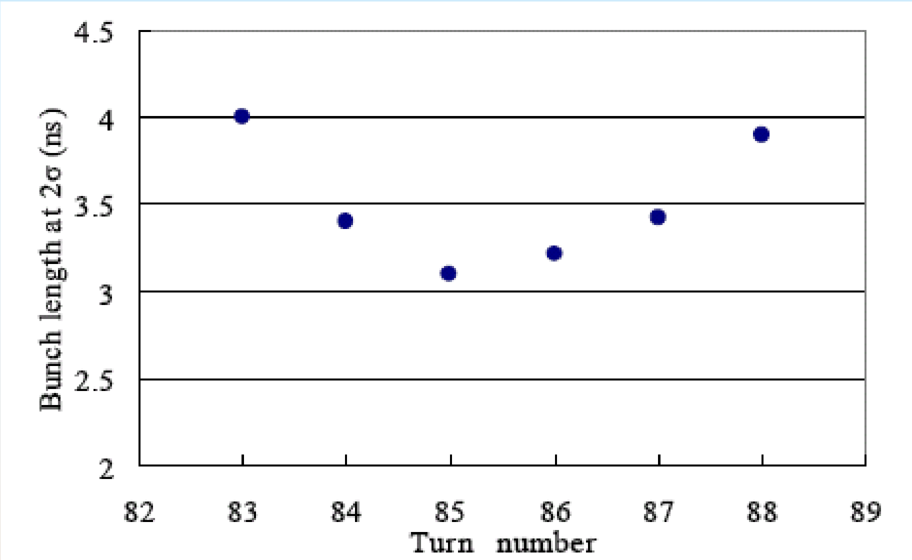


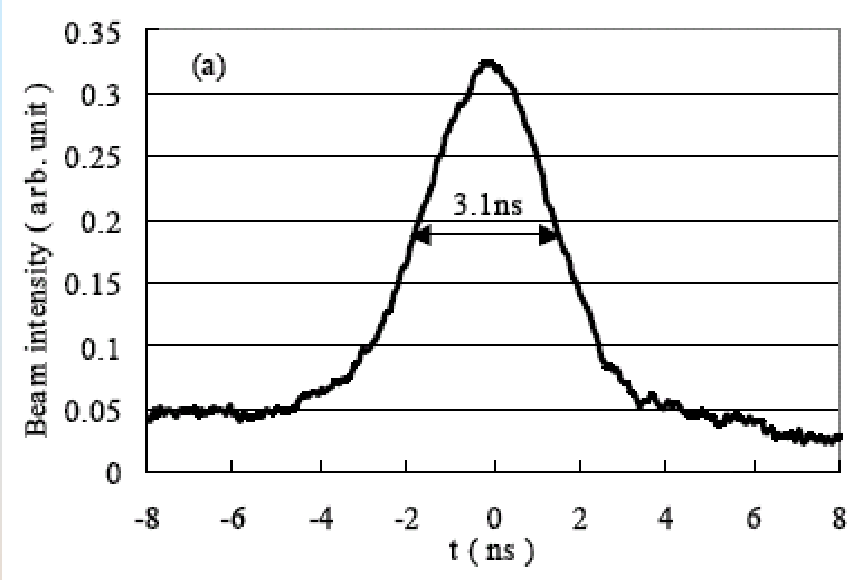
Bunch Rotation of 7 MeV Proton

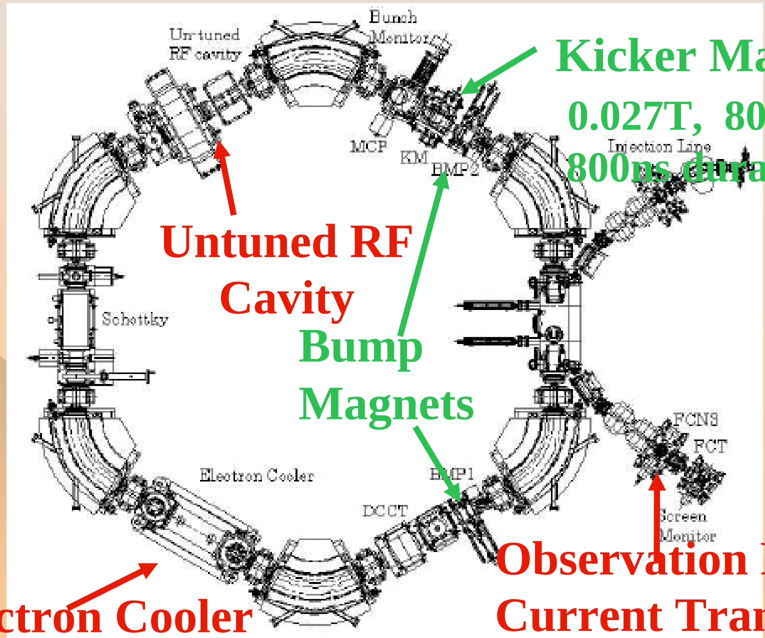


RF field (800 V) is applied to coasting beam after electron cooling and is extracted when the beam is rotated ~90°.

Shortest Pulse Created by Phase Rotation







Kicker Magnet
0.027T, 80ns rise time
800ns duration

Untuned RF Cavity

Bump Magnets

Electron Cooler

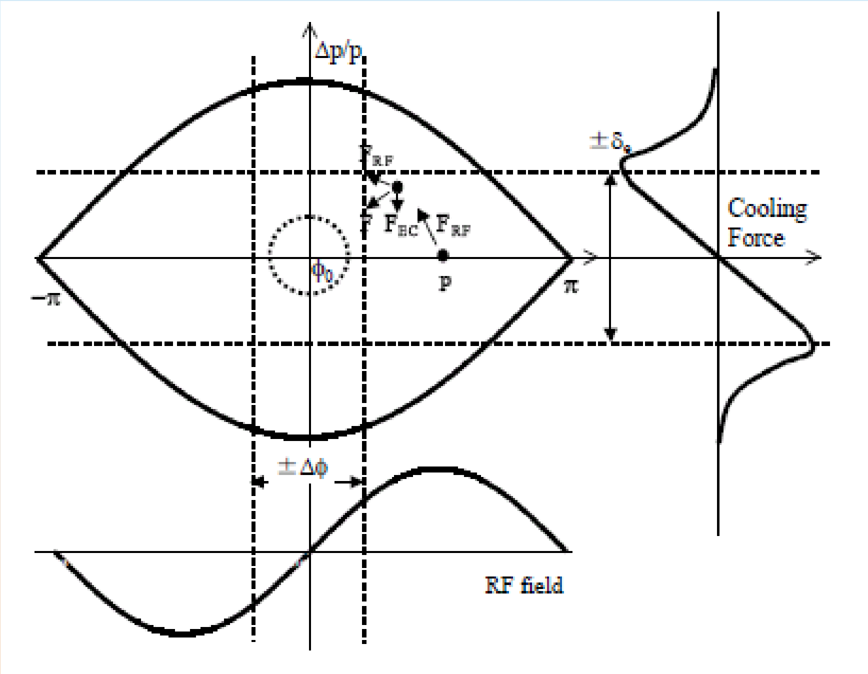
Observation Point by FCT (Fast Current Transformer)

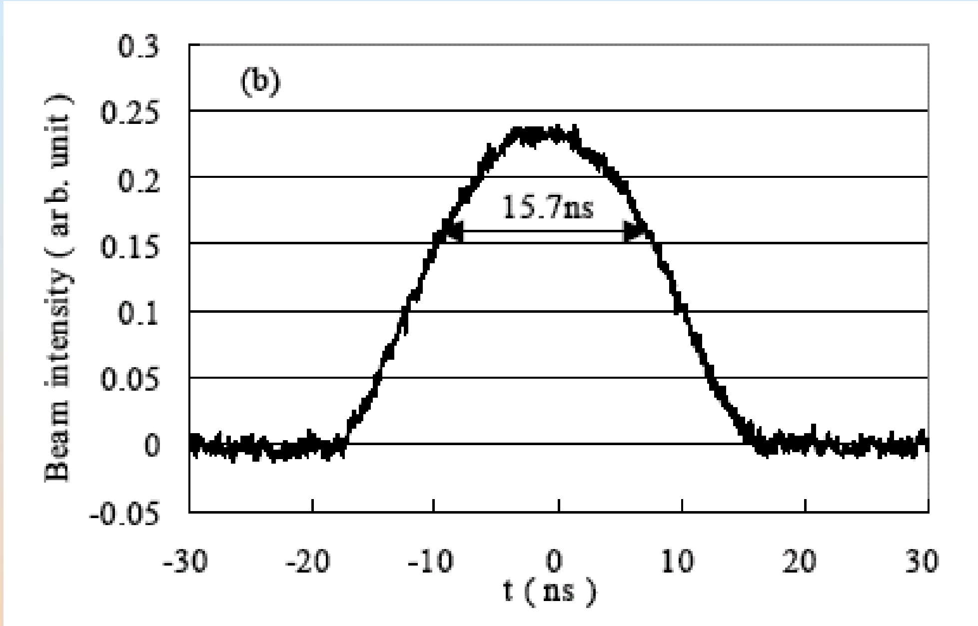
Short bunch duration of 3.1 ns (2σ)
7 MeV proton with Intensity 1.4x 10^8

Extraction efficiency is estimated ~20% due to filamentation.

Improvement of extraction efficiency by application saw tooth RF wave form is expected.

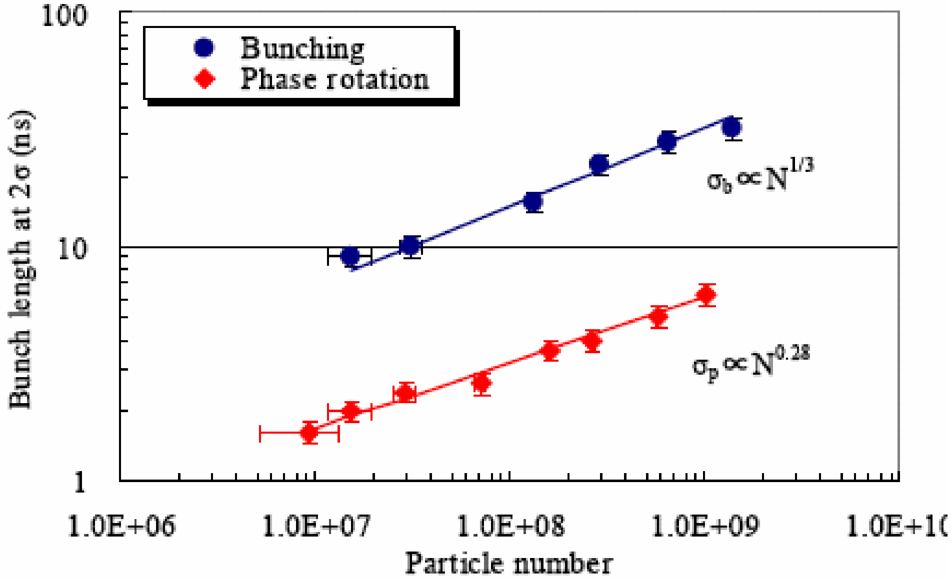
Short Pulse Formation of 7 MeV Proton by Bunching Method at S-LSR

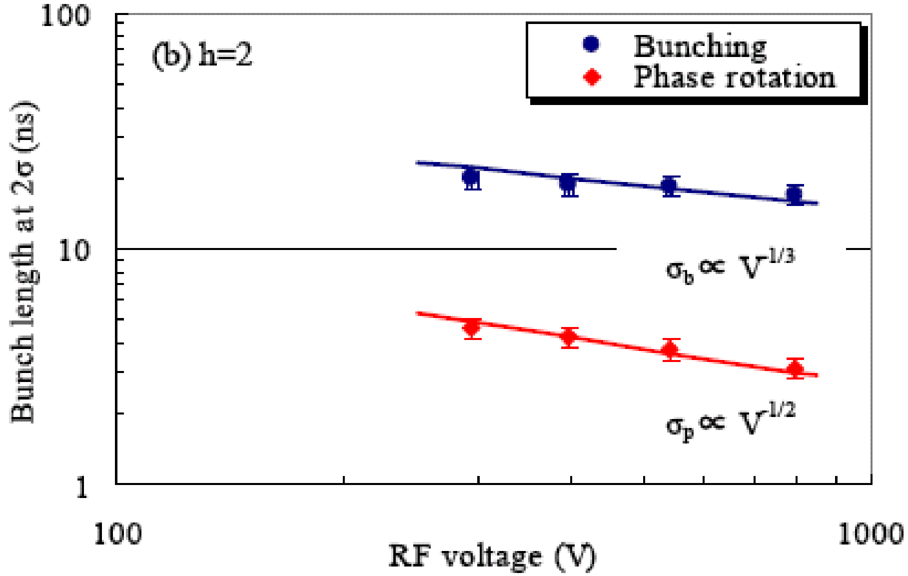




Simultaneous application of RF voltage and electron cooling has resulted in shortest bunch of the duration of ~15.7 ns limited by space charge force. Extraction efficiency is ~100%.

Pulse Length Ever Attained 7 MeV Protons





Particle Number Dependence **RF Voltage Dependence**

DNA Double Strand Break by Laser-produced Proton beam

A. Yogo et al., APL, 94, 181502 (2009)

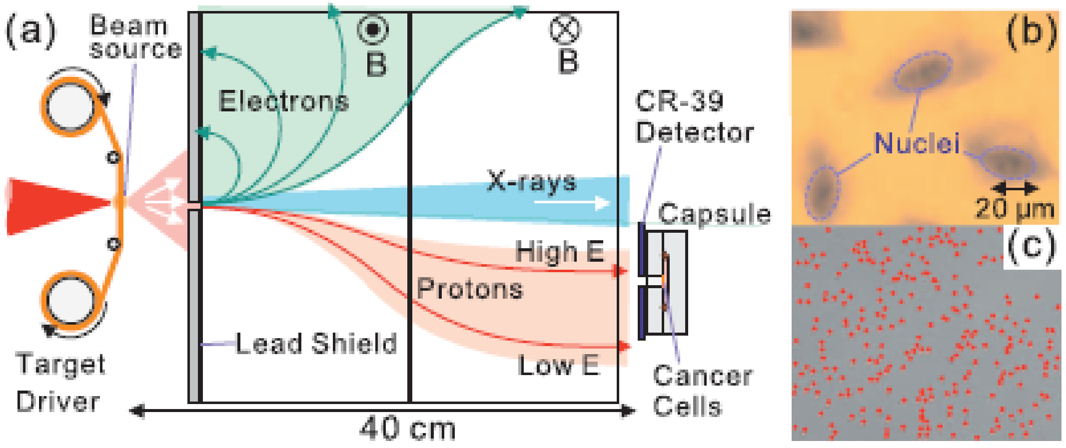


FIG. 1. (Color) (a) A schematic drawing of experimental setup. (b) An image of cancer cells taken by a microscope. (c) A spatial distribution of protons detected by CR-39 in a single laser shot. Each red point represents a single proton bombardment. The screen size is set to be same as that in the frame (b).

Pulse Width 15ns, 20 Gy

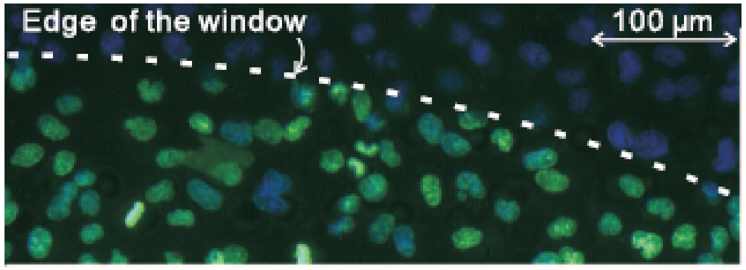
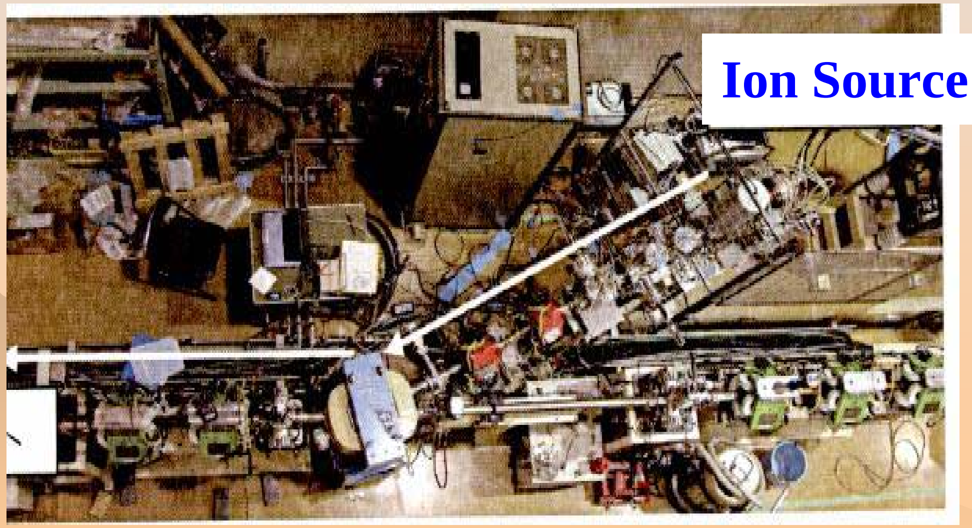
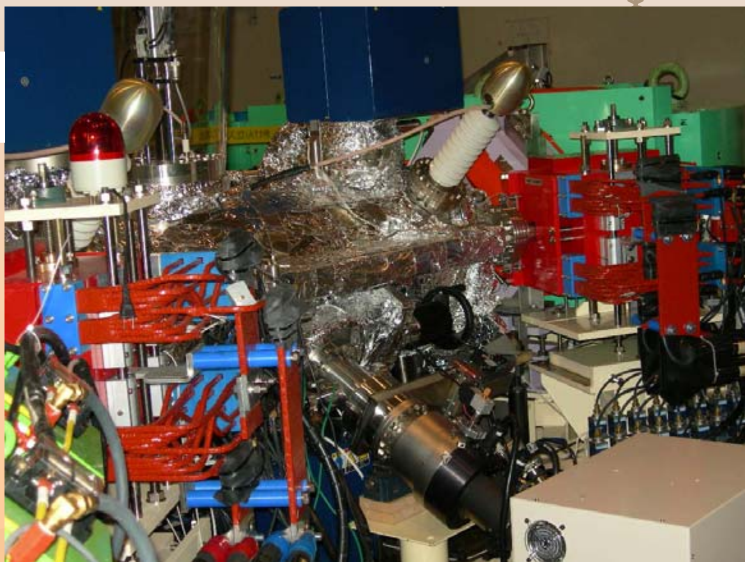


FIG. 3. (Color) γ-H2AX focus formation induced by irradiation of laser-accelerated protons with 20 Gy. γ-H2AX and nucleus are stained with anti-γ-H2AX antibody (green) and DAPI (blue).

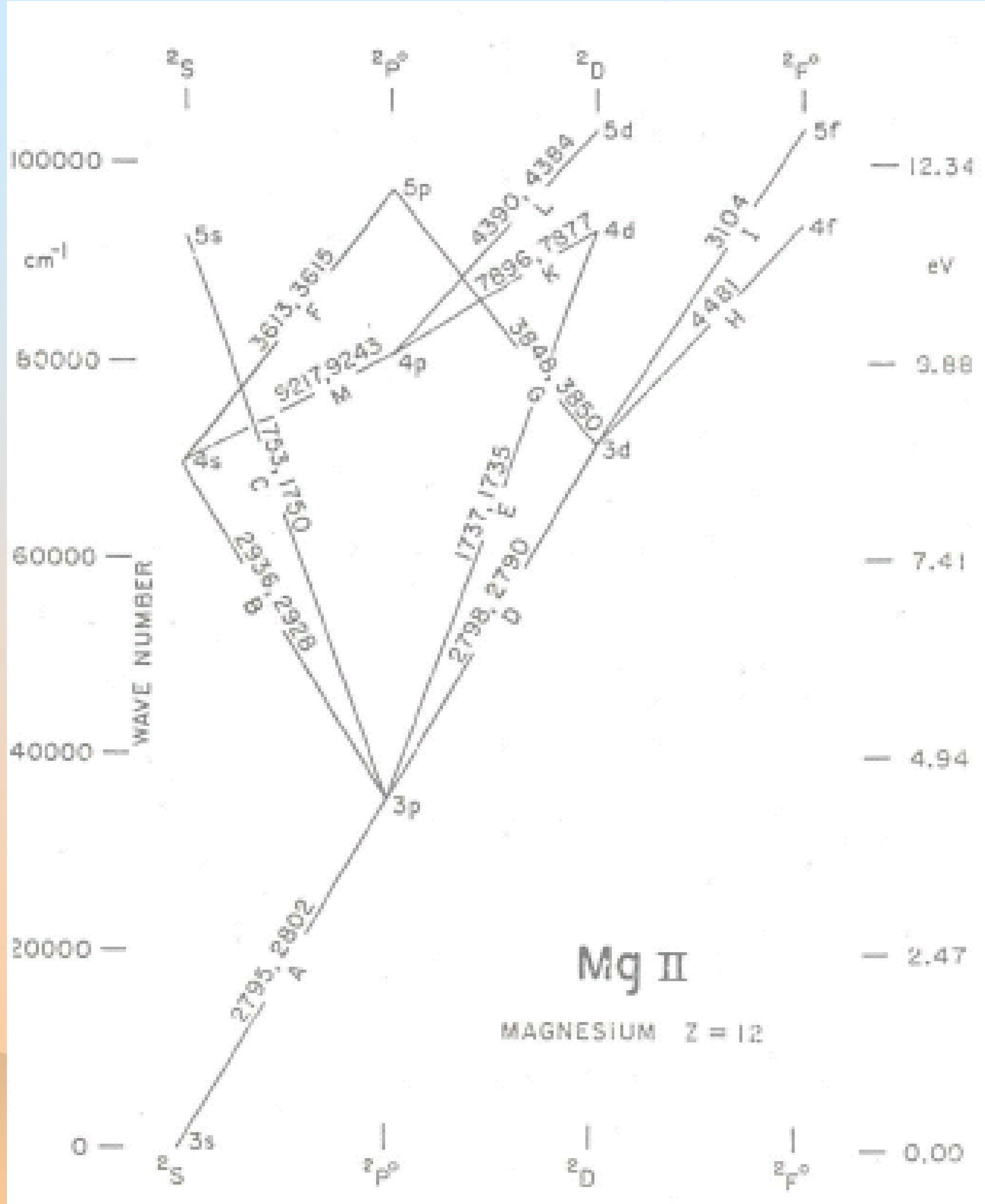
Laser Cooling of $^{24}Mg^{+}$ Ion Beam

$^{24}Mg^{+}$ Ion Source (40 keV)

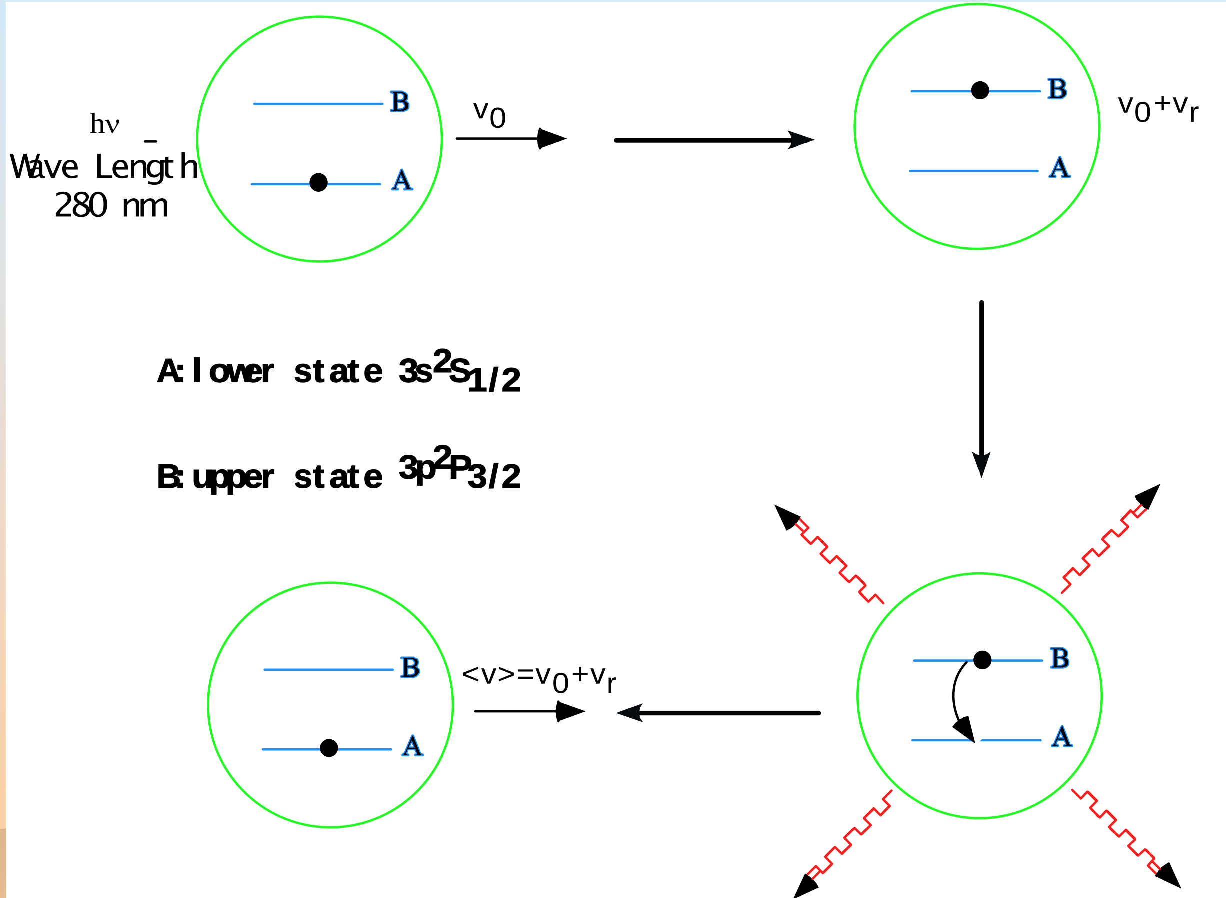




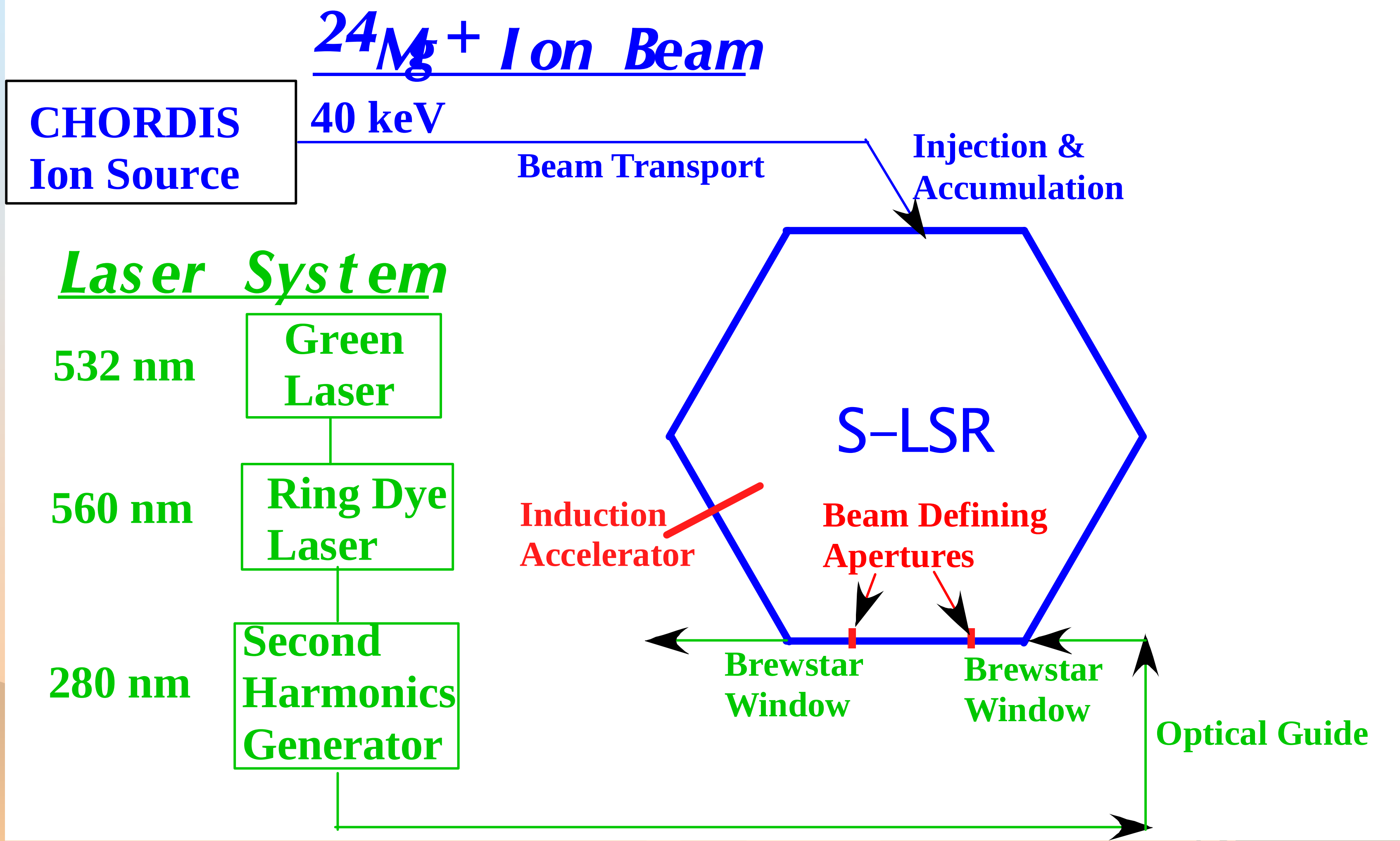
Excited States of Mg Ion



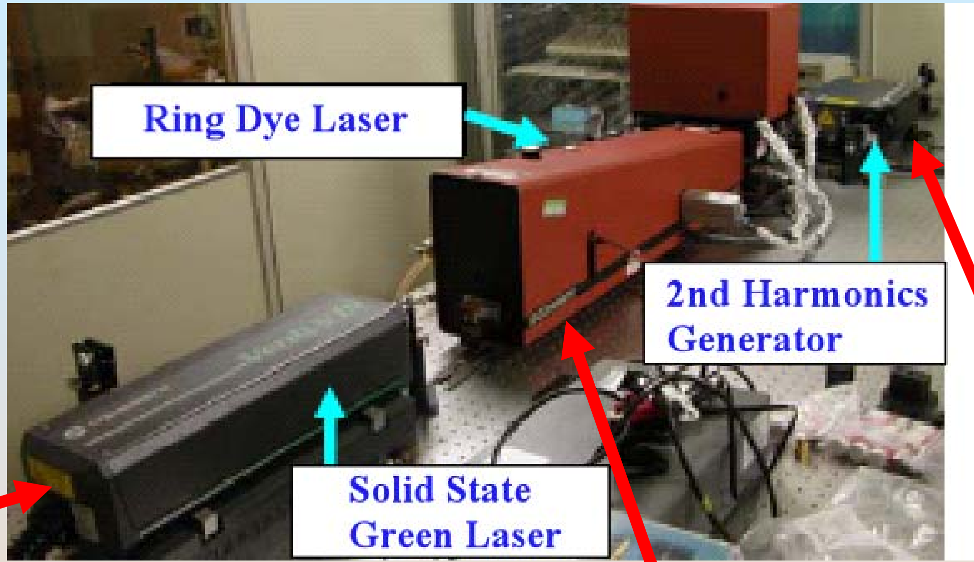
Principle of Laser Cooling (Longitudinal)

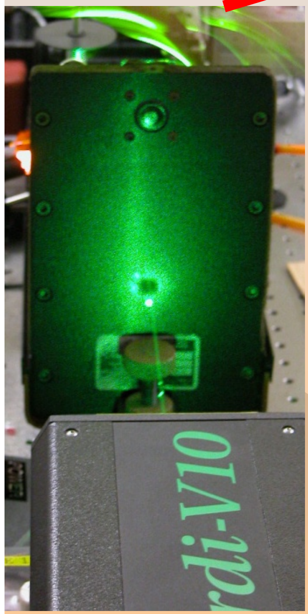


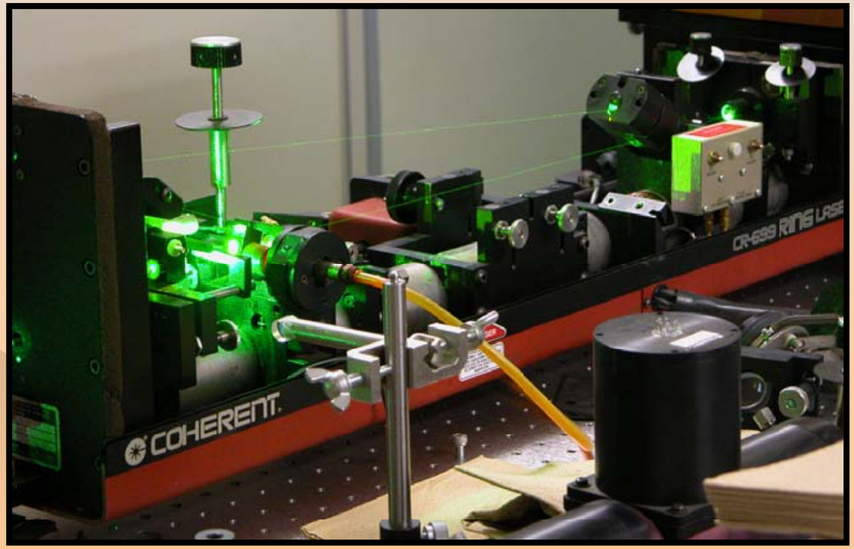
Block Diagram of Laser Cooling at S-LSR

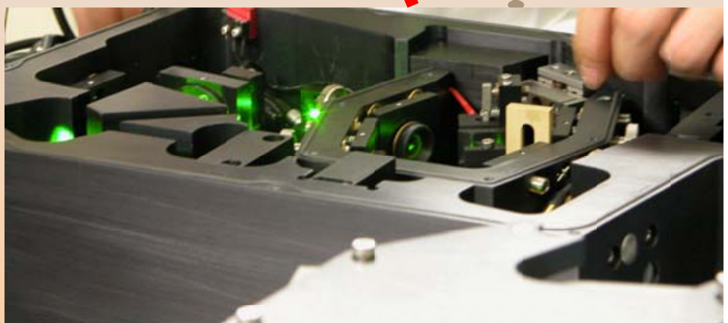


Laser System for Cooling









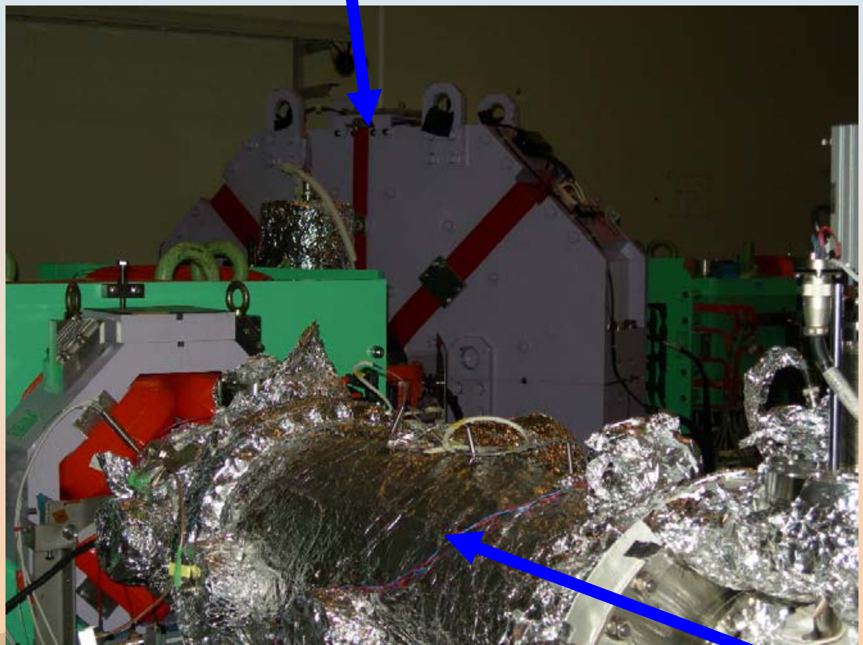
Typical Laser Parameters

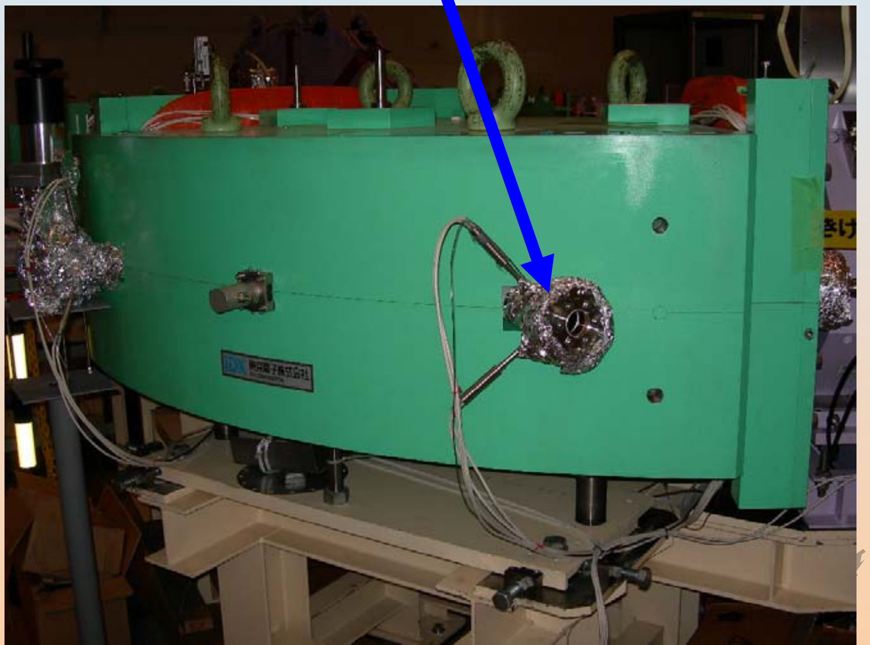
Output of Solid State Laser	8.1 W
Output of Dye Laser	645 mW
Output of Second Harmonics Generator	47 mW
Wavelength	~279 nm
Saturation Intensity	254 mW/cm^2

Laser Cooling Section of S-LSR

Induction Accelerator

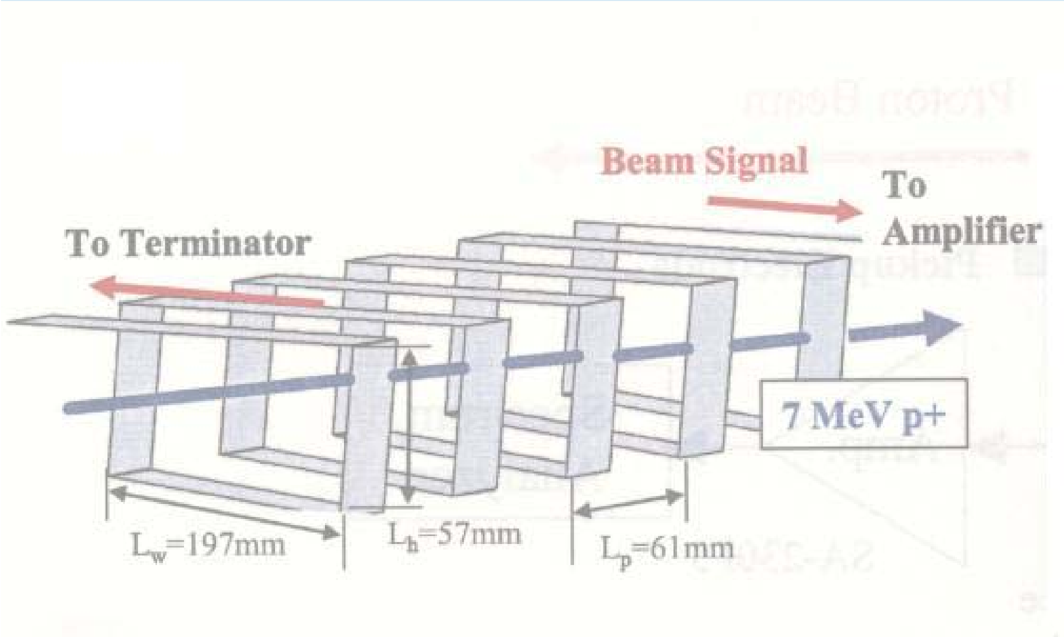
Window for Laser port





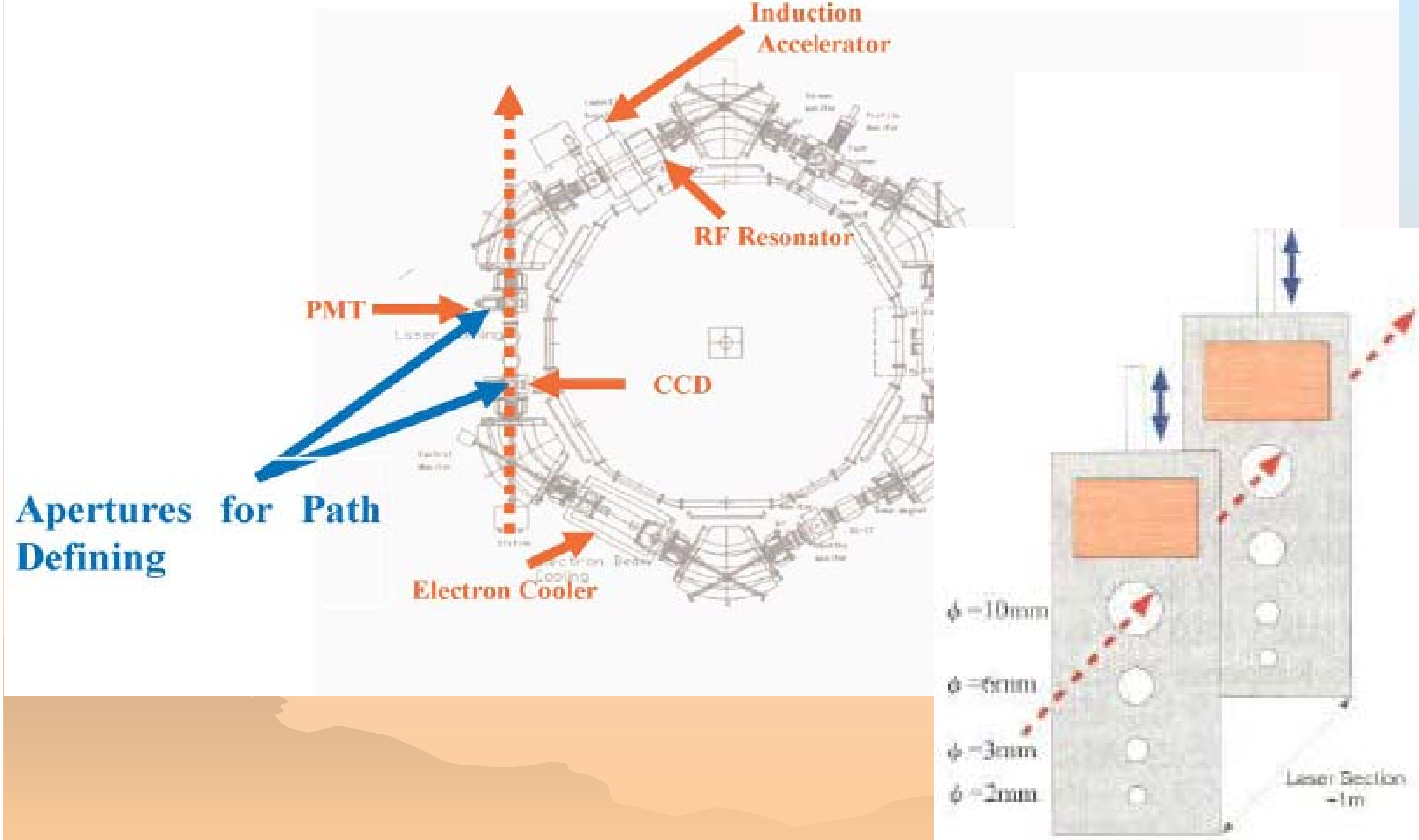
Helical Schottky Pick-up for 7 MeV proton is installed here.

Structure of Schottky Pick-Up



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

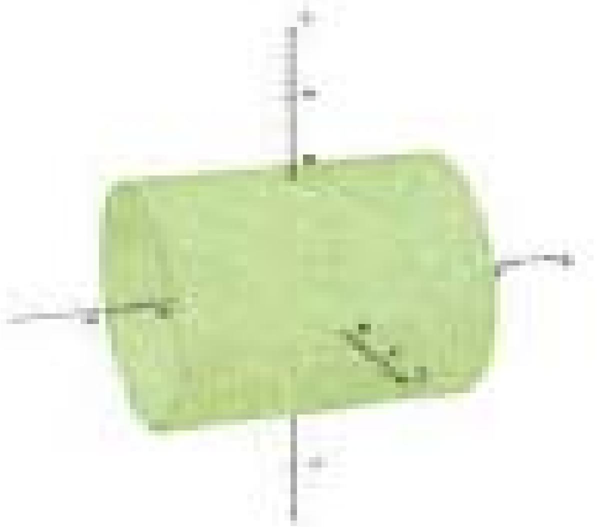
Overlapping of Ion and Laser Beams



By T. Ishikawa

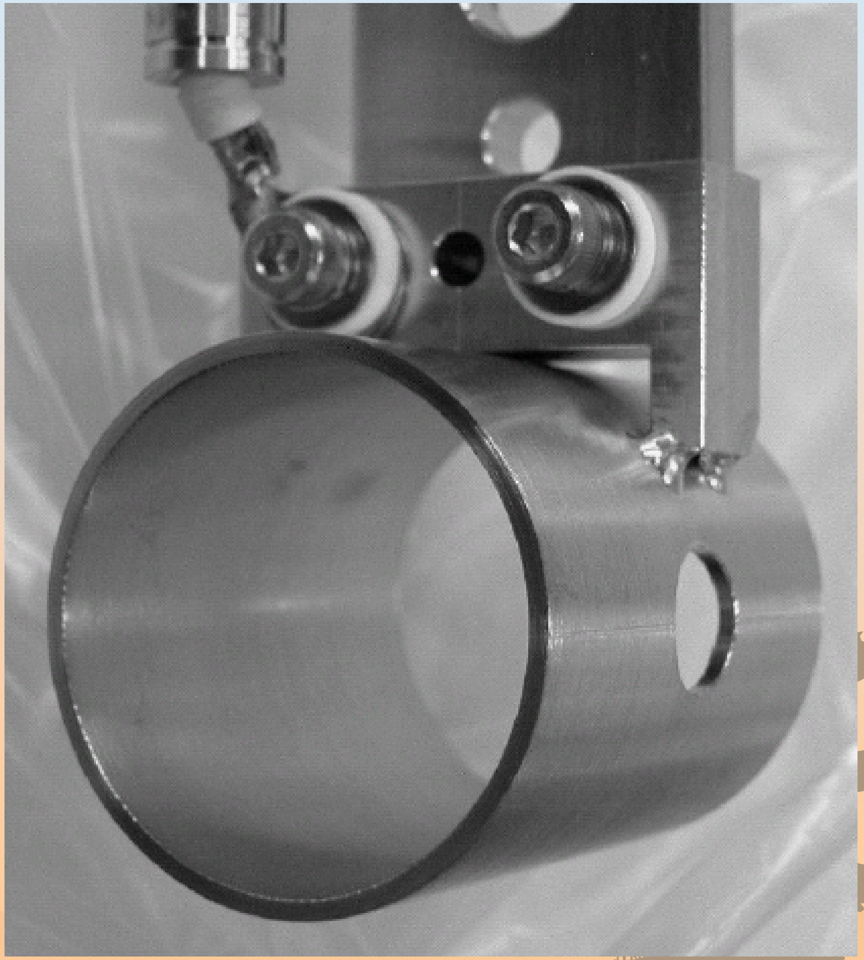
Post Acceleration Tube (PAT)

-Energy Sweep is applied for Distribution Measurement-

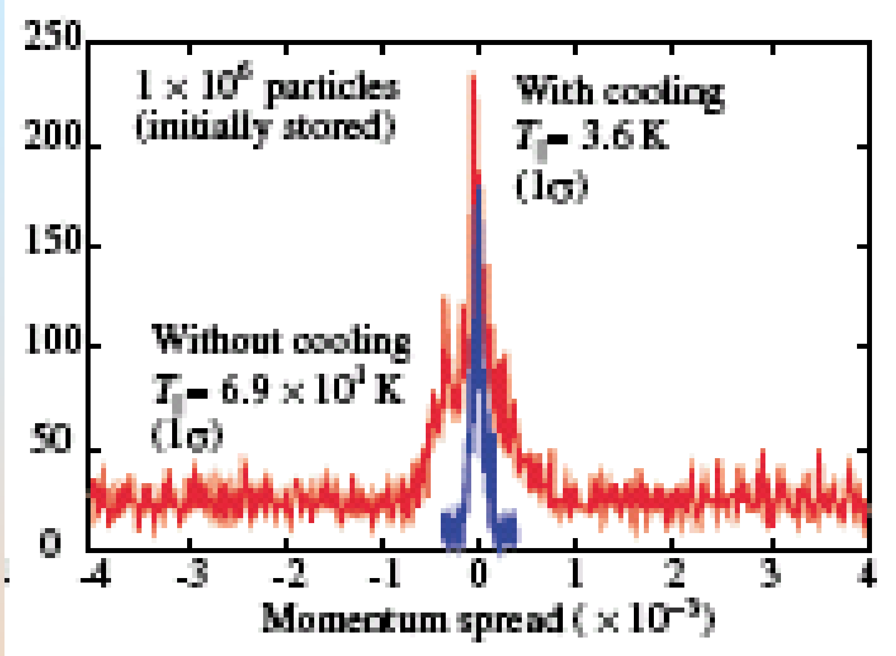


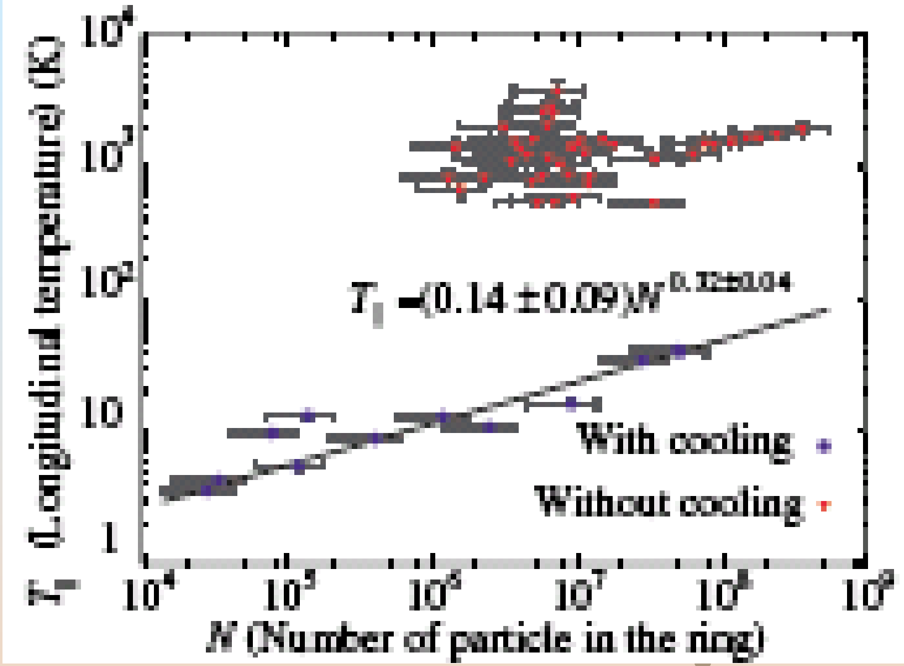
Specification of PAT

Inner Diameter	ϕ35 mm
Outer Diameter	ϕ38 mm
Length	44 mm
Observation Hole	ϕ10 mm



Laser Cooling of Coasting Beam at S-LSR





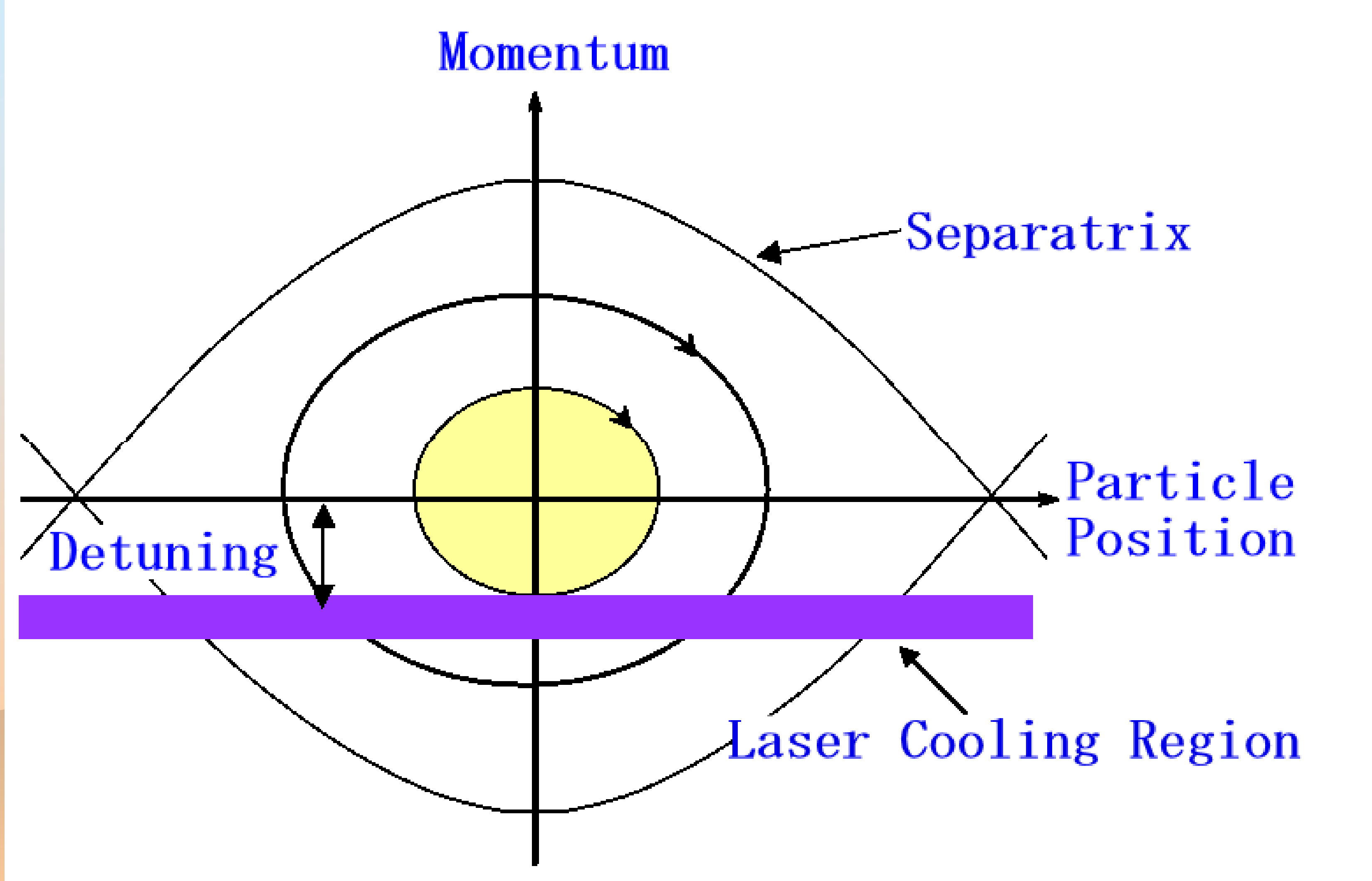
$$k_B T_L = m v_0^2 \left(\frac{\Delta p}{p} \right)^2$$

$$T_L \propto N^{0.32 \pm 0.04}$$

$$T_L = 0.02 T_\perp$$

$$\Lambda_{IBS} \propto N \Big/ T_H T_V \sqrt{T_L} \longrightarrow T_L \propto N^{0.4}$$

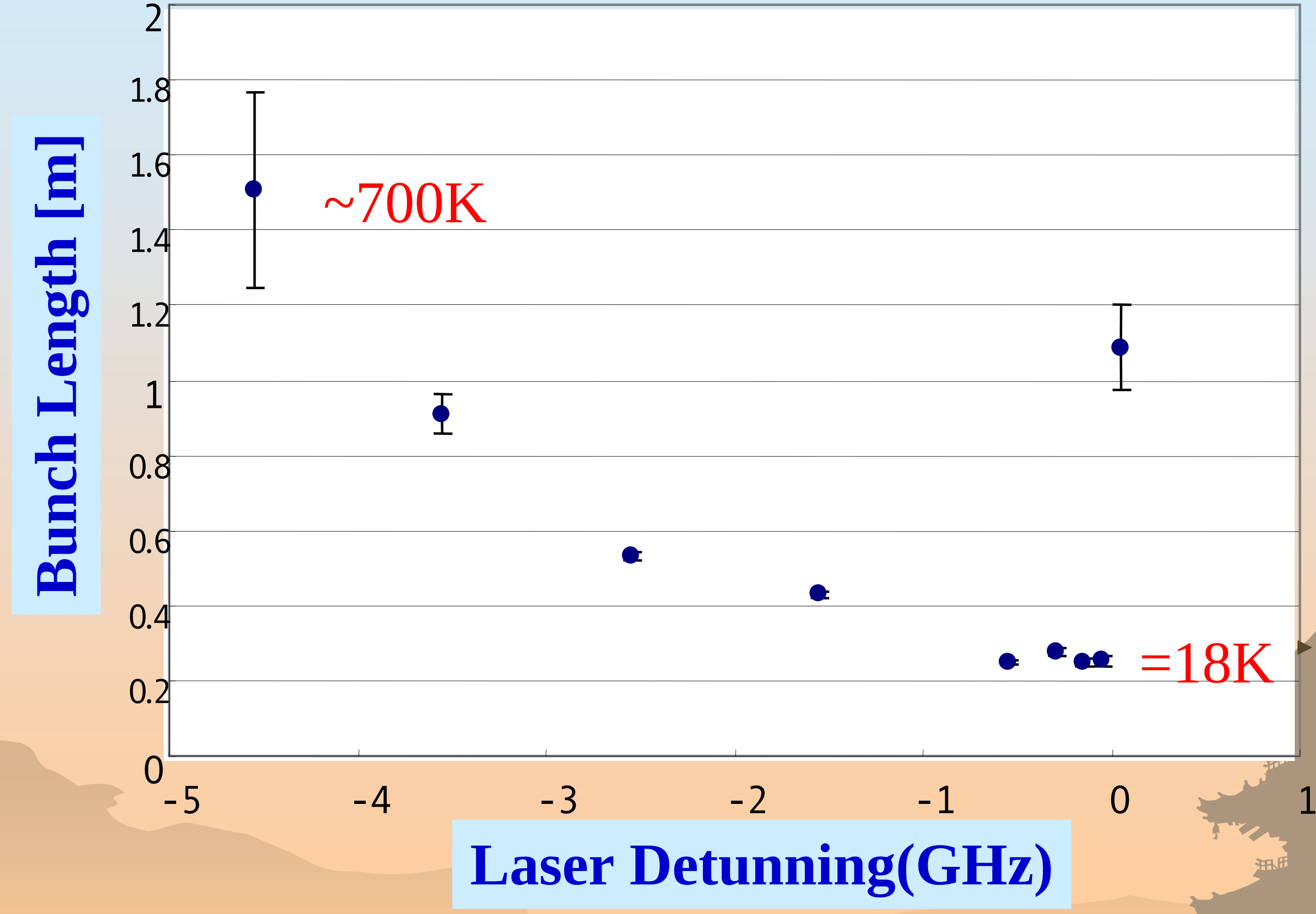
Bunched Beam Cooling



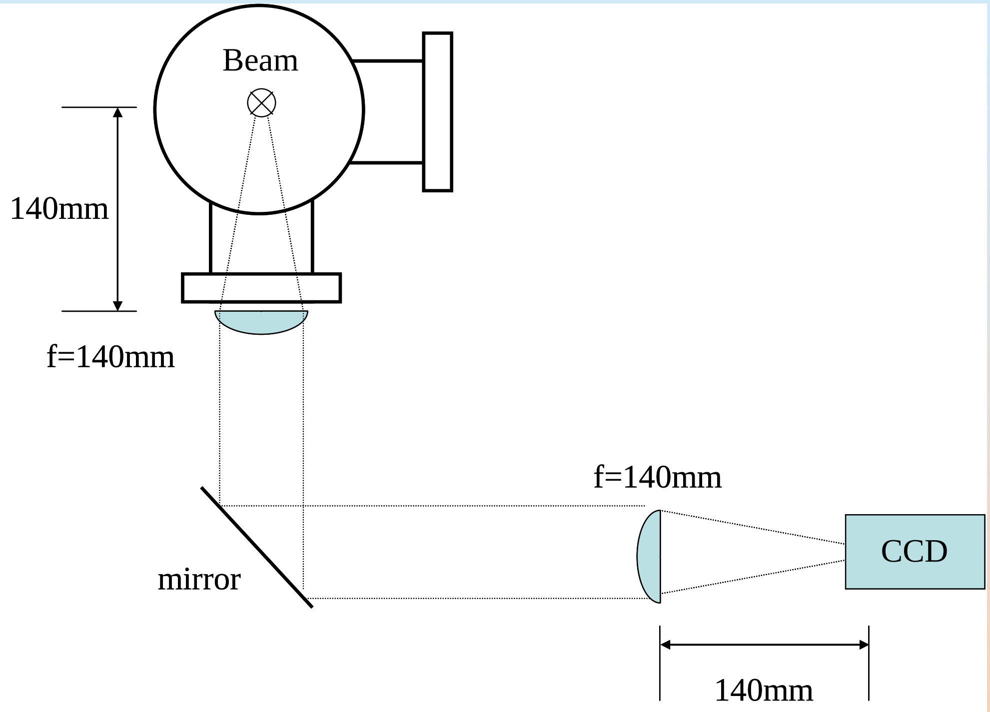
M. Nakao, Master Thesis, Kyoto University (2008)

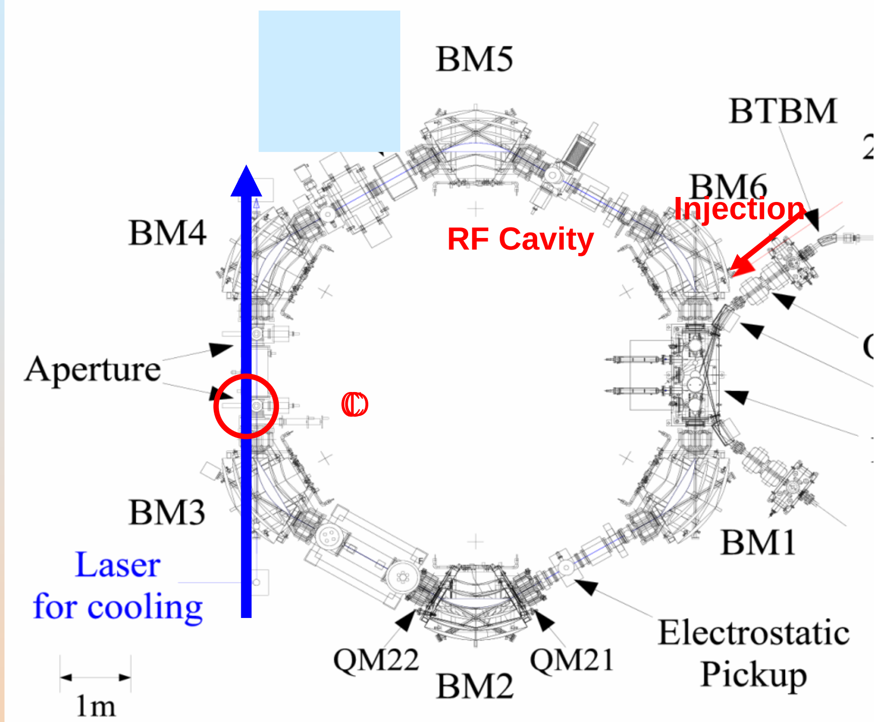
Result of Bunched Beam Cooling

N=6x10^{6} , RF Freq=125.96kHz(h=5) , Voltage=3.06V



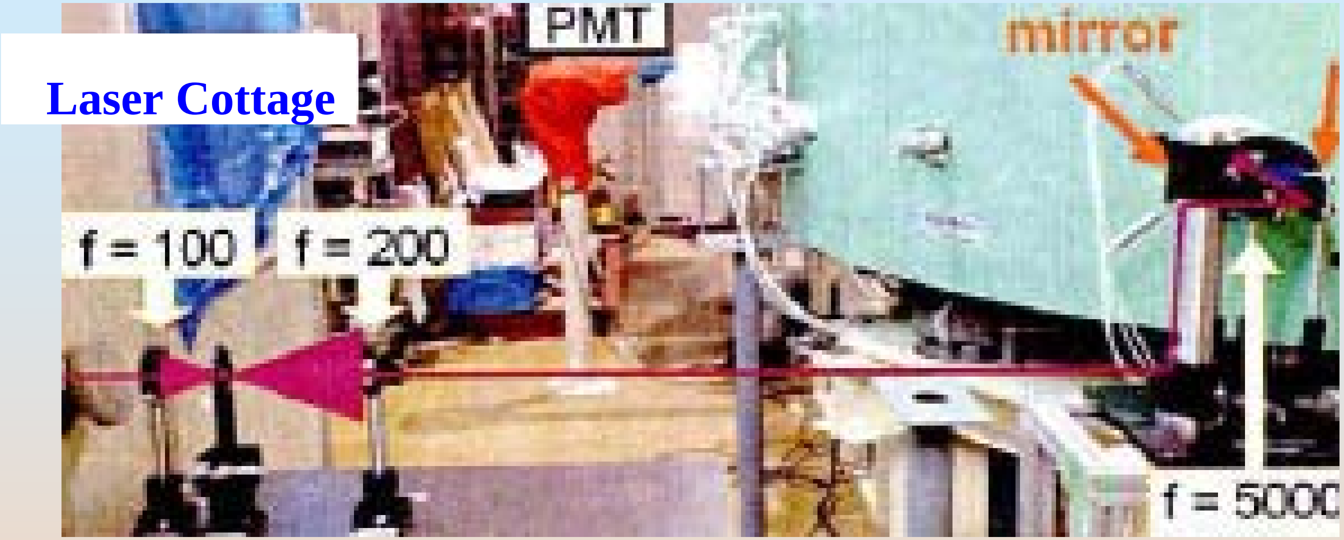
Observation of Transverse Beam Size by CCD Camera

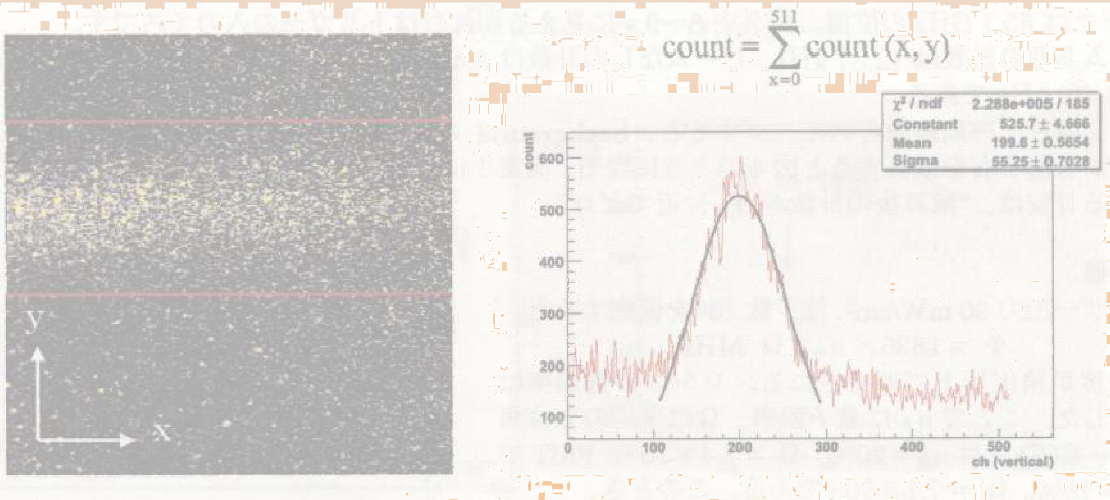


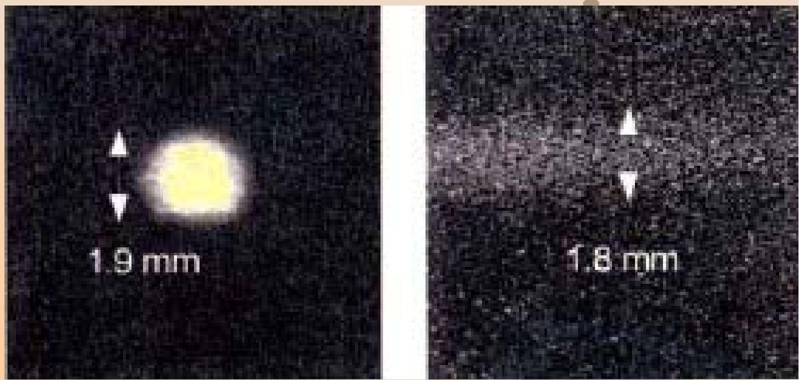


Cooled CCD Camera
(Hamamatsu Photonics C7190-11W)

Ion Observation with Emitted Light







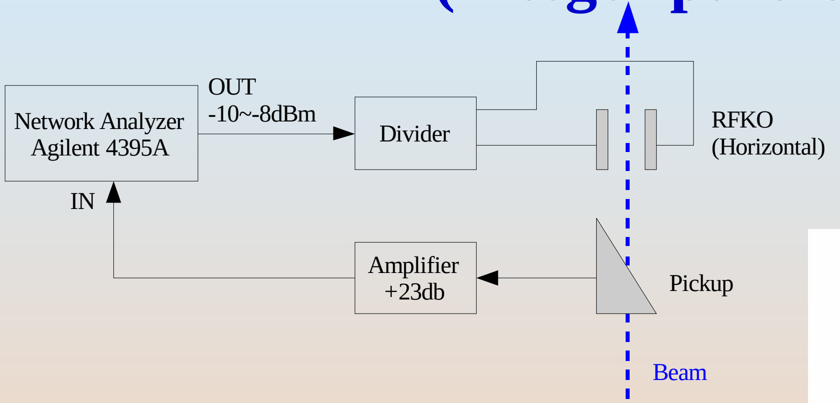
Laser Profile

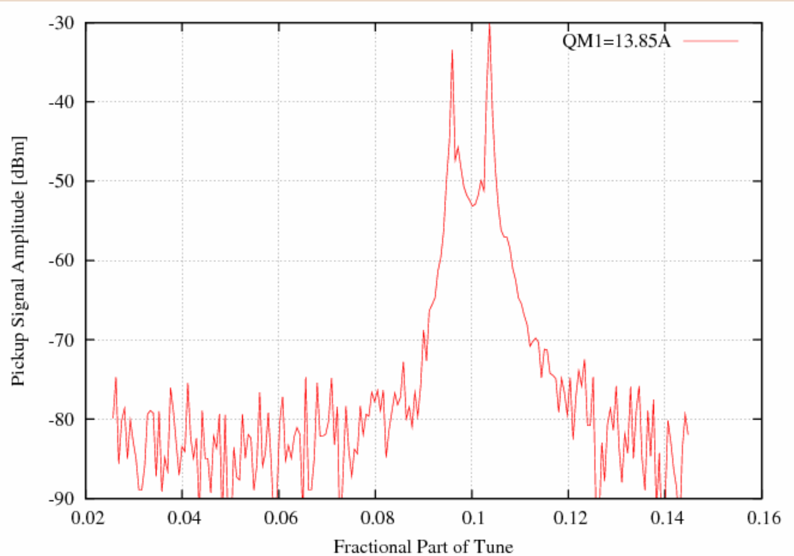
Fluorescent light from the ion beam

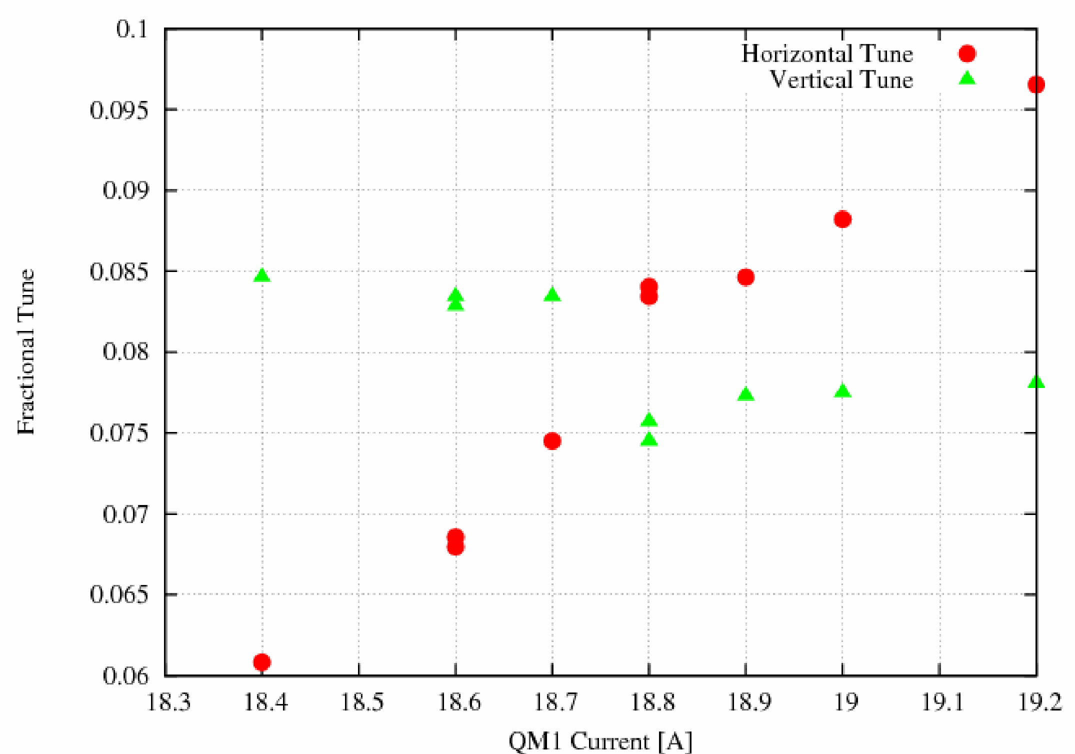
Measurement of Fractional Part of Betatron Tune through Transfer Function Measurement

Beam Transfer Function→Fractional Part of Betatron Tune

(Integer part is obtained from MAD Calculation)



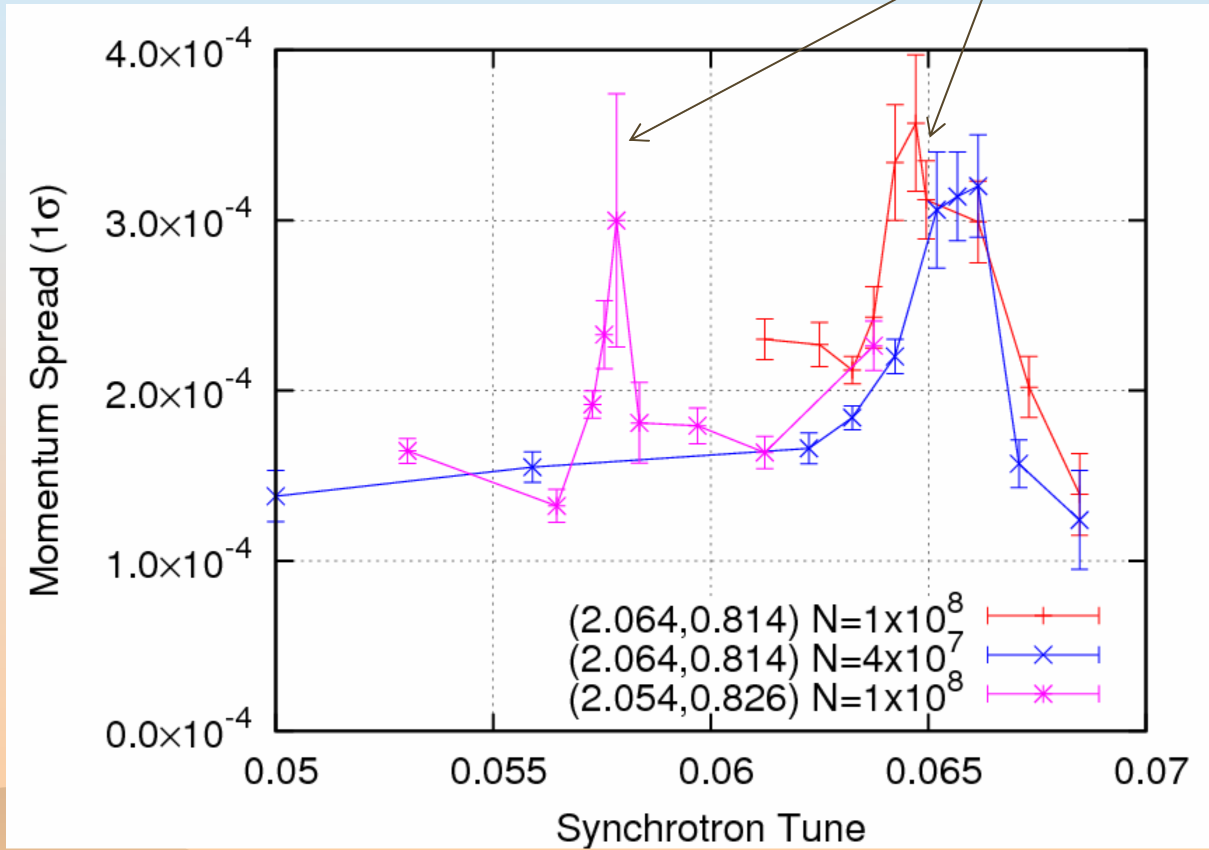




Evidence of Synchro-Betatron Coupling

$(\nu_x,\nu_y,\nu_s)=(2.064, 0.814, 0.065)$
$(2.054, 0.826, 0.057)$

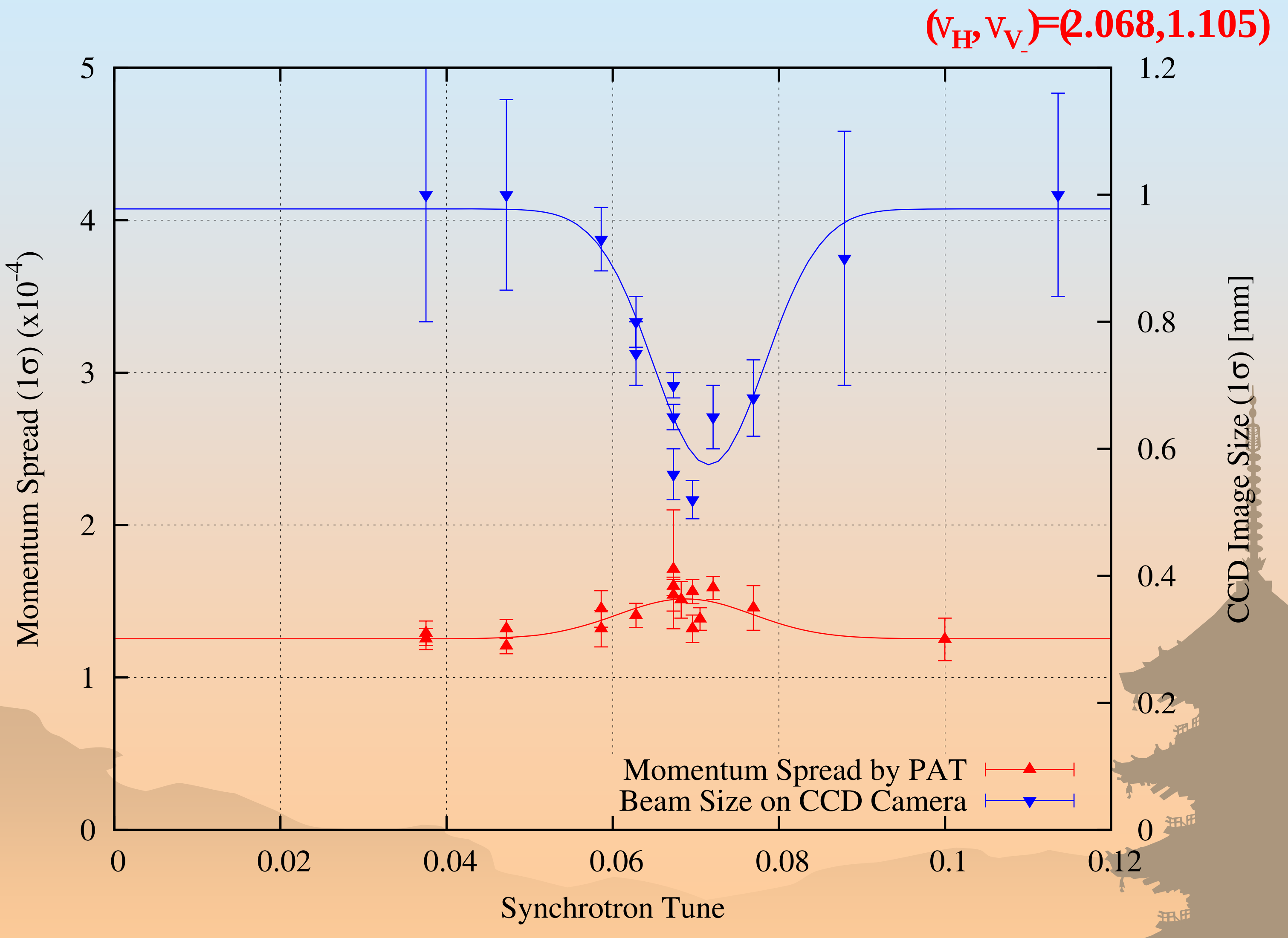
Resonant Increase of Momentum Spread



Heat is considered to be trasferred from horizontal direction.

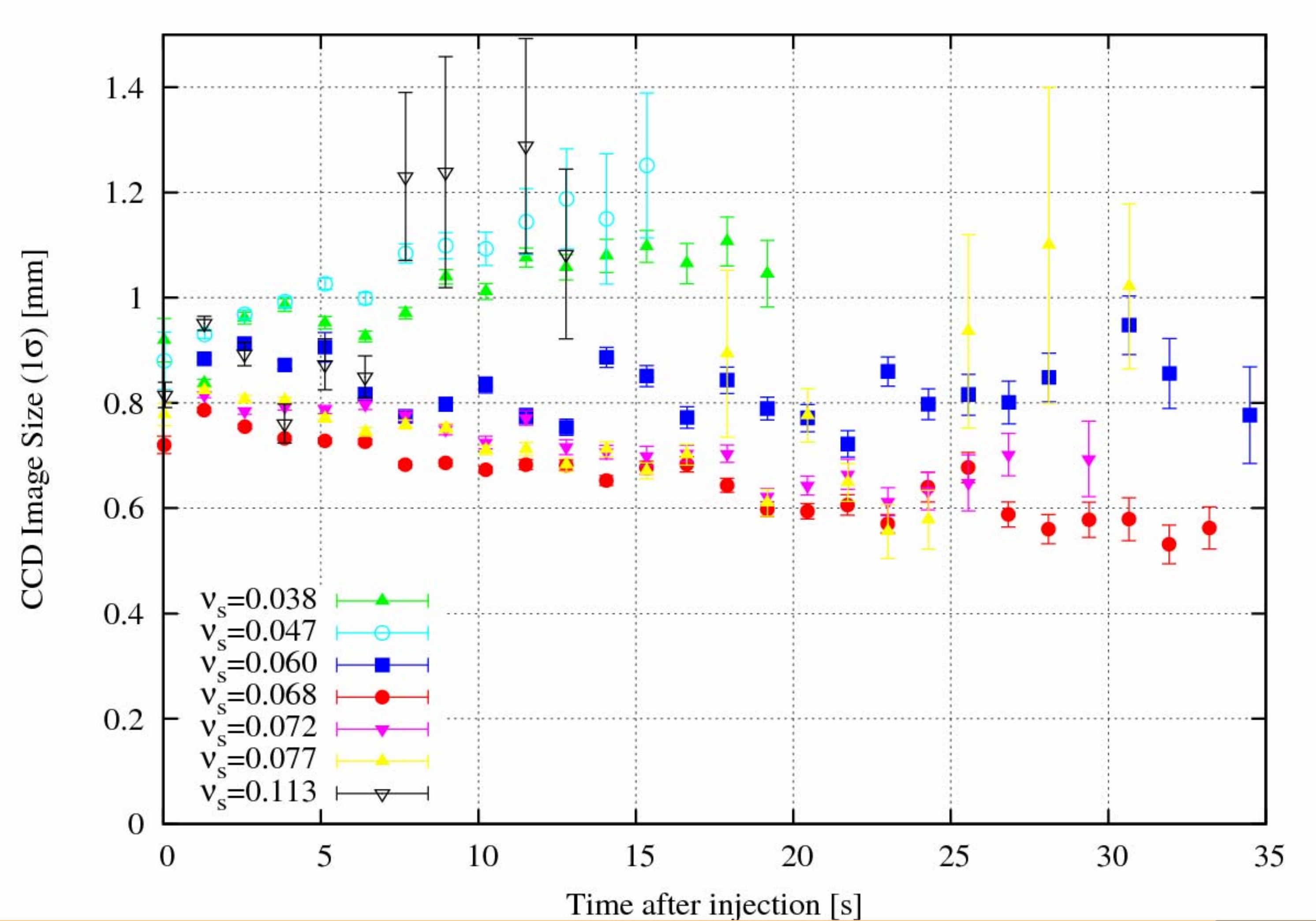
Reduction of horizontal beam size is to be observed.

Transverse Laser Cooling by Synchro-Betatron Coupling



Time Variation of Transverse Beam Size for Various Synchrotron Tune

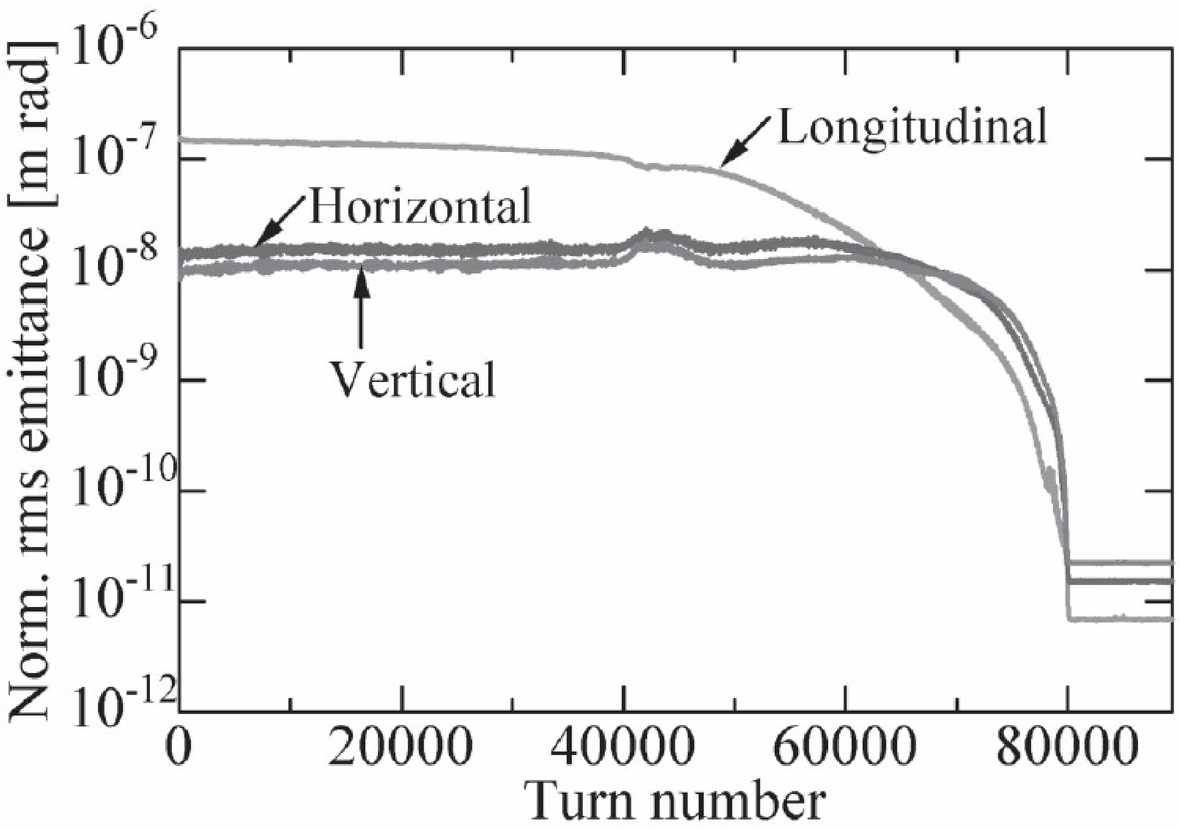
$(\nu_H, \nu_V)=(2.068, 1.105)$



Parameters of the Present Experiments

Ion	**$^{24}Mg^{+}$**
Kinetic Energy	**40keV**
Betatron Tune	**(2.068,1.105)** **(2.098,1.103)**
Synchrotron Tune	**0.0376~0.1299**
Initial Particle Number	**3×10^{7}**
Initial Momentum Spread	**7×10^{-4}**
Laser Detuning	**-0.1GHz±0.005GHz**
Laser Power	**13mW~20mW(S-LSR Exit)**

3 D Laser Cooling expected by Simulation



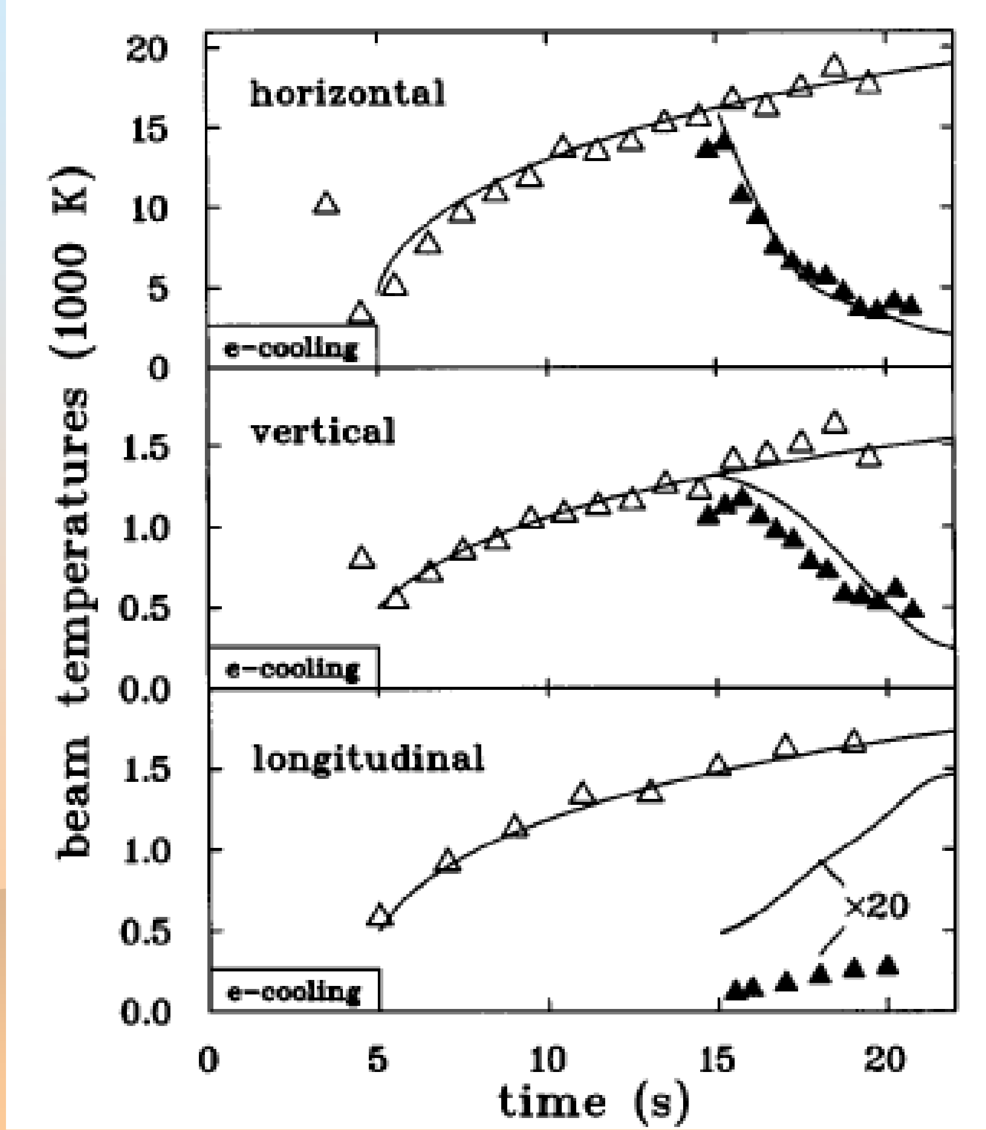
ν_H-ν_s=integer,

ν_H-ν_V=integer

Y. Yuri and H.Okamoto,
Phys. Rev. ST-AB, 8,114201 (2005)

Indirect Transverse Laser Cooling with Intra-beam Scattering (coasting beam)

H.-J. Meisner et al., PRL, 77, 623-626 (1996)



3 x 10^7 ions

σ~0.5 mm

Indirect Transverse Laser Cooling with Intra-beam Scattering (bunched beam)

H.-J. Meisner et al., NIM, A383, 634-636 (1996)

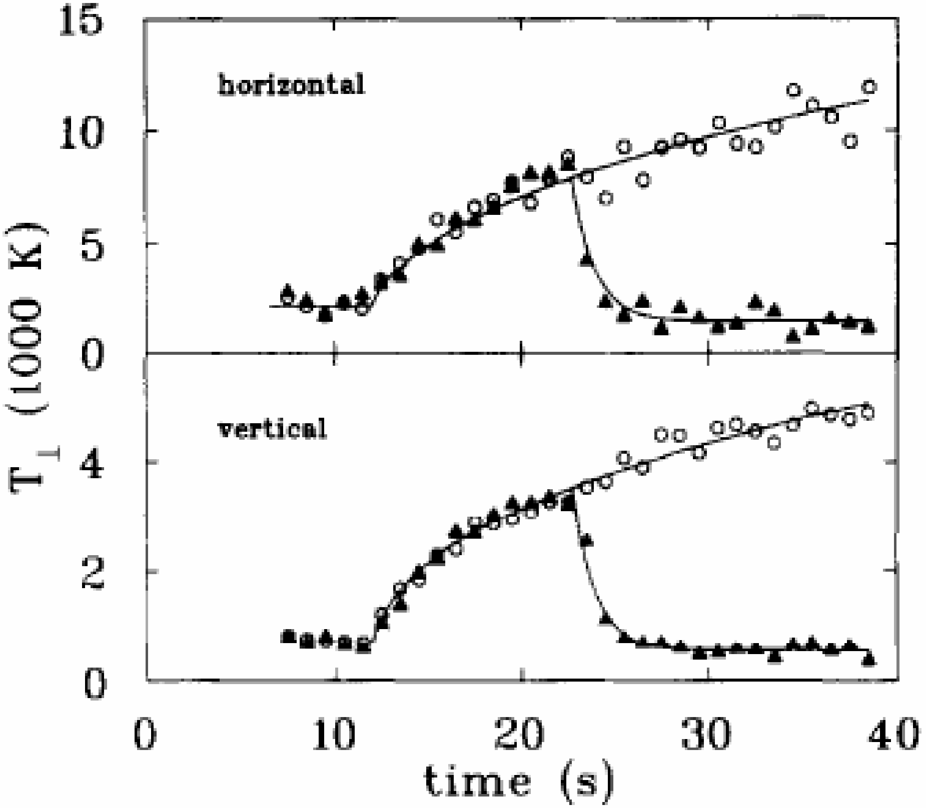
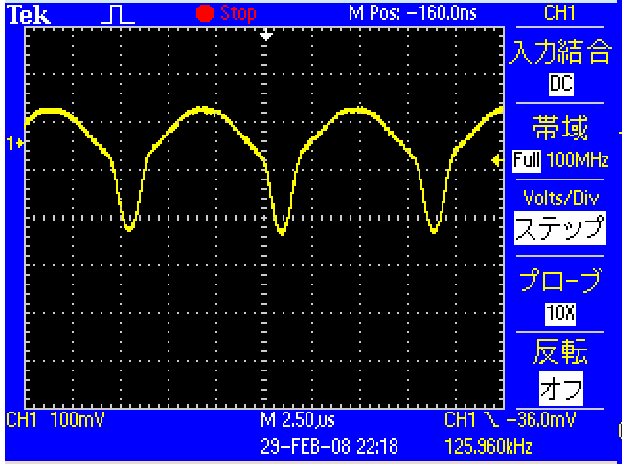


Fig. 1. Temporal evolution of the transverse beam temperatures. The open circles show the beam "blowup" after switching off the electron cooling at t = 12 s. The filled triangles represent corresponding measurements with laser cooling switched on at t = 22 s. The solid lines are shown to guide the eye.

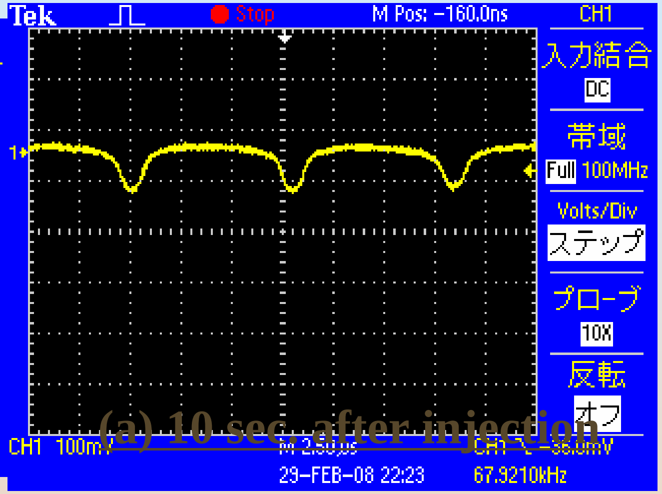
2×10^6 ions

σ~1.0 mm

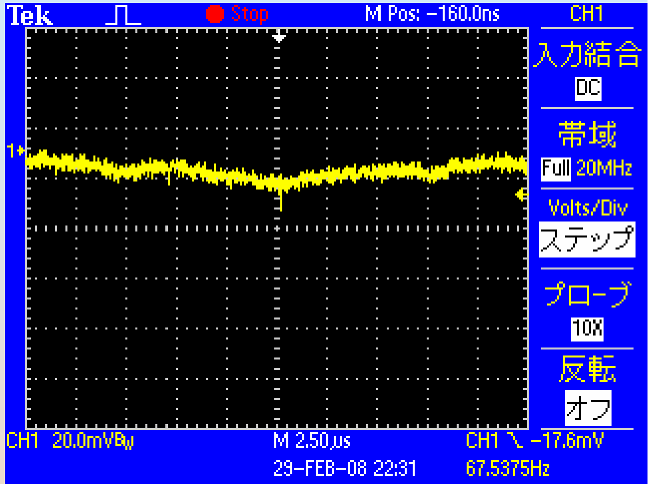
Two components in longitudinally laser cooled beam



(a) 10 sec. after injection

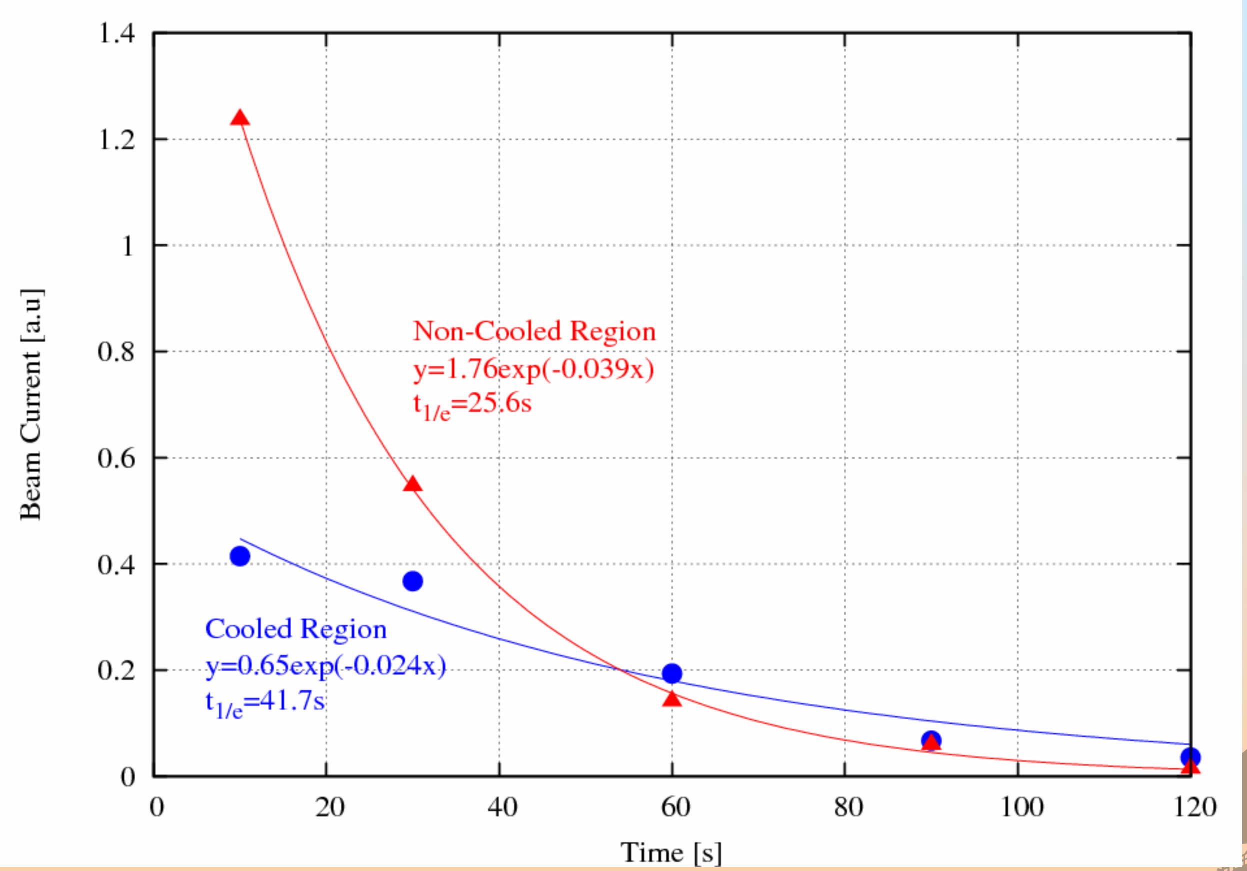


(b) 60 sec. after injection



(c) 150 sec. after injection
(almost no beam)

Life of two components



Attainment at S-LSR on Beam Cooling

1. Electron Beam Cooling
   - One dimensional ordering of 7 MeV proton at ordered state: $T_{\parallel}$~2 K. $T_{\perp}$~11 K coasting beam (how about bunched beam?)
   - Creation of short bunch length ~3 nsec.

   → possibility of Bio-cell vertical irradiation course
2. Laser Cooling
   - Coasting beam $T_{\parallel}$ ~ 3.6K
   - Bunched beam on resonance $T_{\parallel}$~24 K, $T_{\perp}$~200 K

     off resonance $T_{\parallel}$~15 K, $T_{\perp}$~600 K

Future Perspectives

1. Suppression of intra-beam scattering → Reduction of Particle Number

   →Increase of beam monitor sensitivity

2. Experimental Demonstration of 3-dimensional laser cooling by coupling among 3 degrees of freedom (L-H, H-V have been already performed)

3. Toward much lower temperature

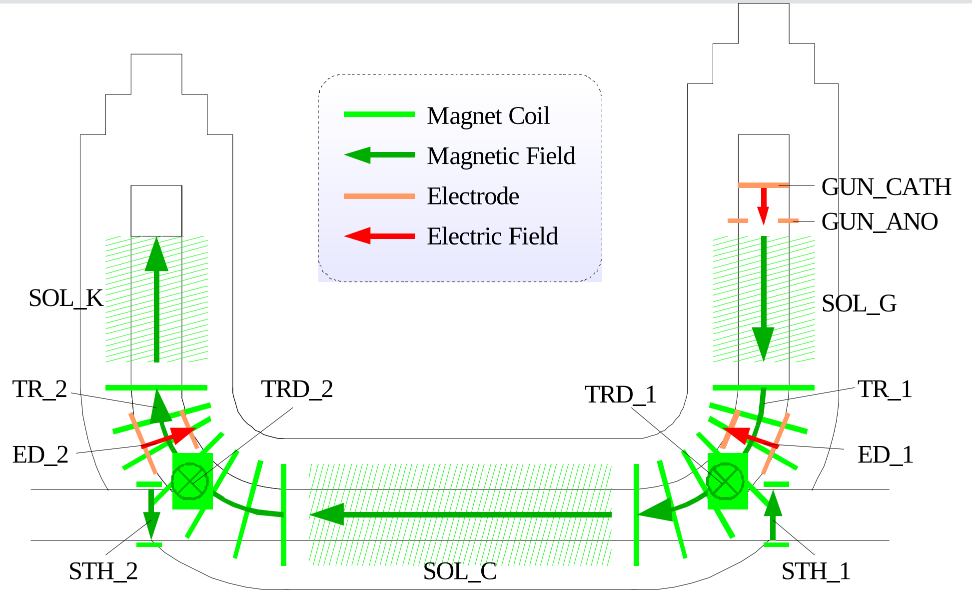
   Optimization of longitudinal bunched beam cooling selecting out the hot ion beams

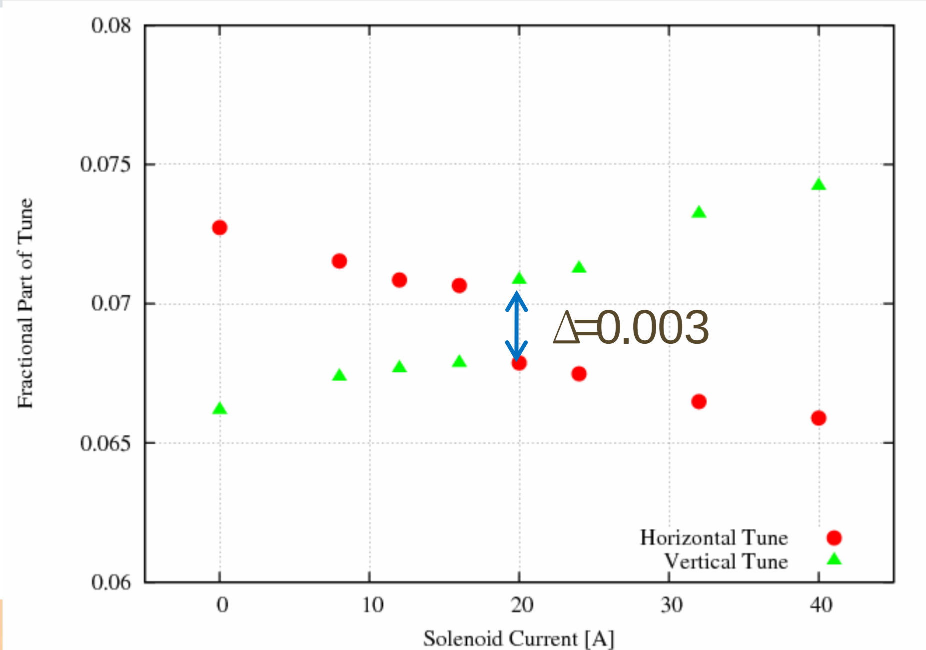
   Capability of pre-cooling by electron beam cooling

   In such a happy situation as realize one dimensional crystal

   →suppression of shear heating by dispersionless lattice

H-V Coupling with a Solenoid Field





Solenoid Field of Electron Cooler (Effective Length=1.2 m)

Operating Point ~ (2.073, 1.067)

By H. Souda

Capability of pre-cooling by EC (simulation with Betacool)

Ion Beam Temperature

$$k_B T_{i\|} = m_i c^2 \beta^2 \left(\frac{\Delta p}{p}\right)^2$$

$$k_B T_{i\perp} = m_i c^2 \beta^2 \gamma^2 \frac{\nu\epsilon}{R}$$

$$T_{i\|} = 80\text{meV} = 930\text{K}$$

$$T_{ih} = 120\text{meV} = 1400\text{K}$$

$$T_{iv} = 150\text{meV} = 2000\text{K}$$

Electron Beam Temperature assuming expansion factor 3)

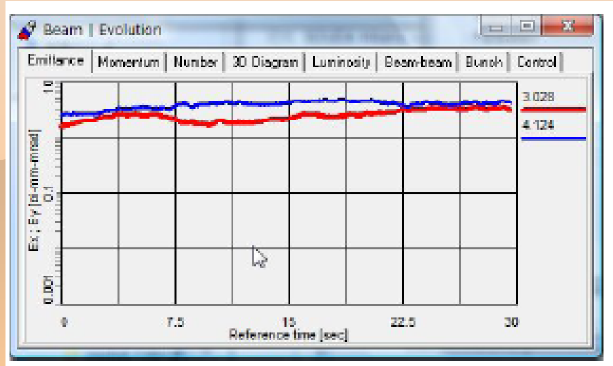
$$k_B T_{e\|} = \frac{(kT_{cath})^2}{m_e c^2 \beta^2 \gamma^2}$$

$$k_B T_{e\perp} = \frac{kT_{cath}}{\alpha_{exp}}$$

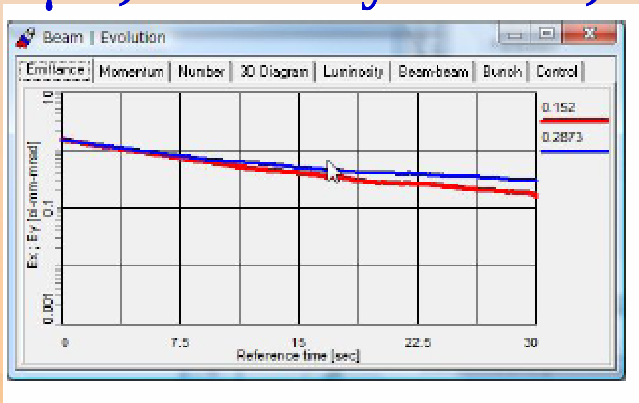
$$T_{e\|} = 5\text{meV} = 58\text{K}$$

$$T_{e\perp} = 30\text{meV} = 350\text{K}$$

Effect of pre-cooling (perbiance 2.3μP, Intensity 1 x 10^7, B~40 G)

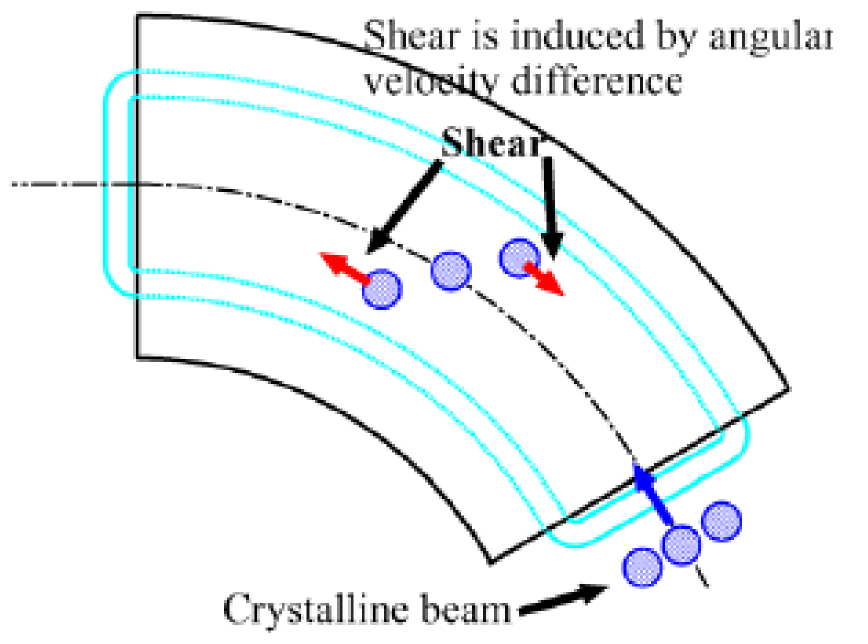


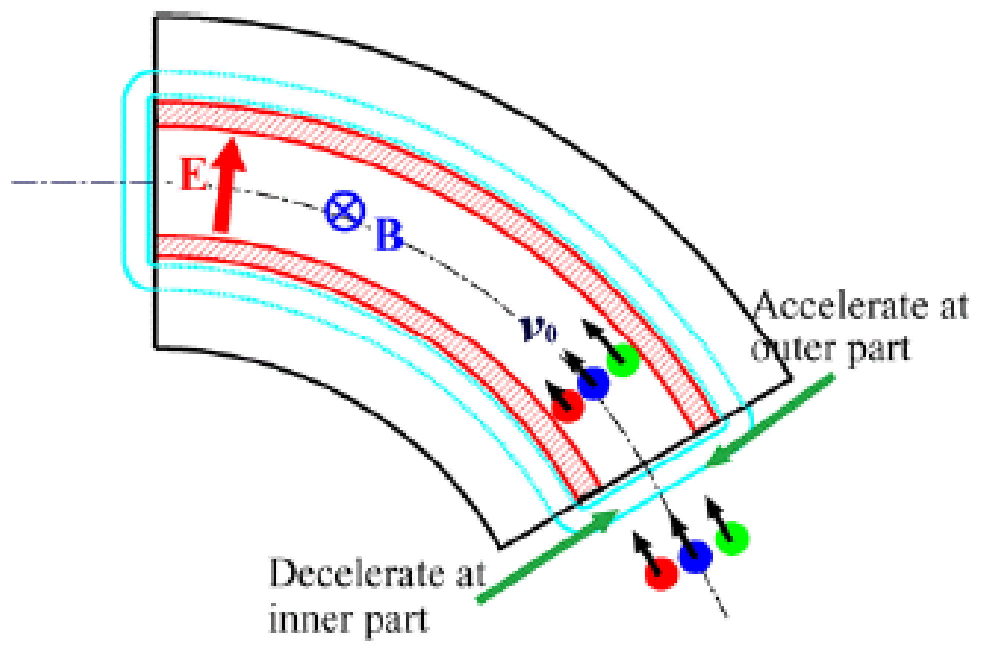
I_e=2μA (extraction 0.9 V)



I_e=300μA (extraction 25V)

Shear Heating and Dispersion Suppressor





W. Henneberg (Ann.Phys.,Lpz.(1934) 19335)

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

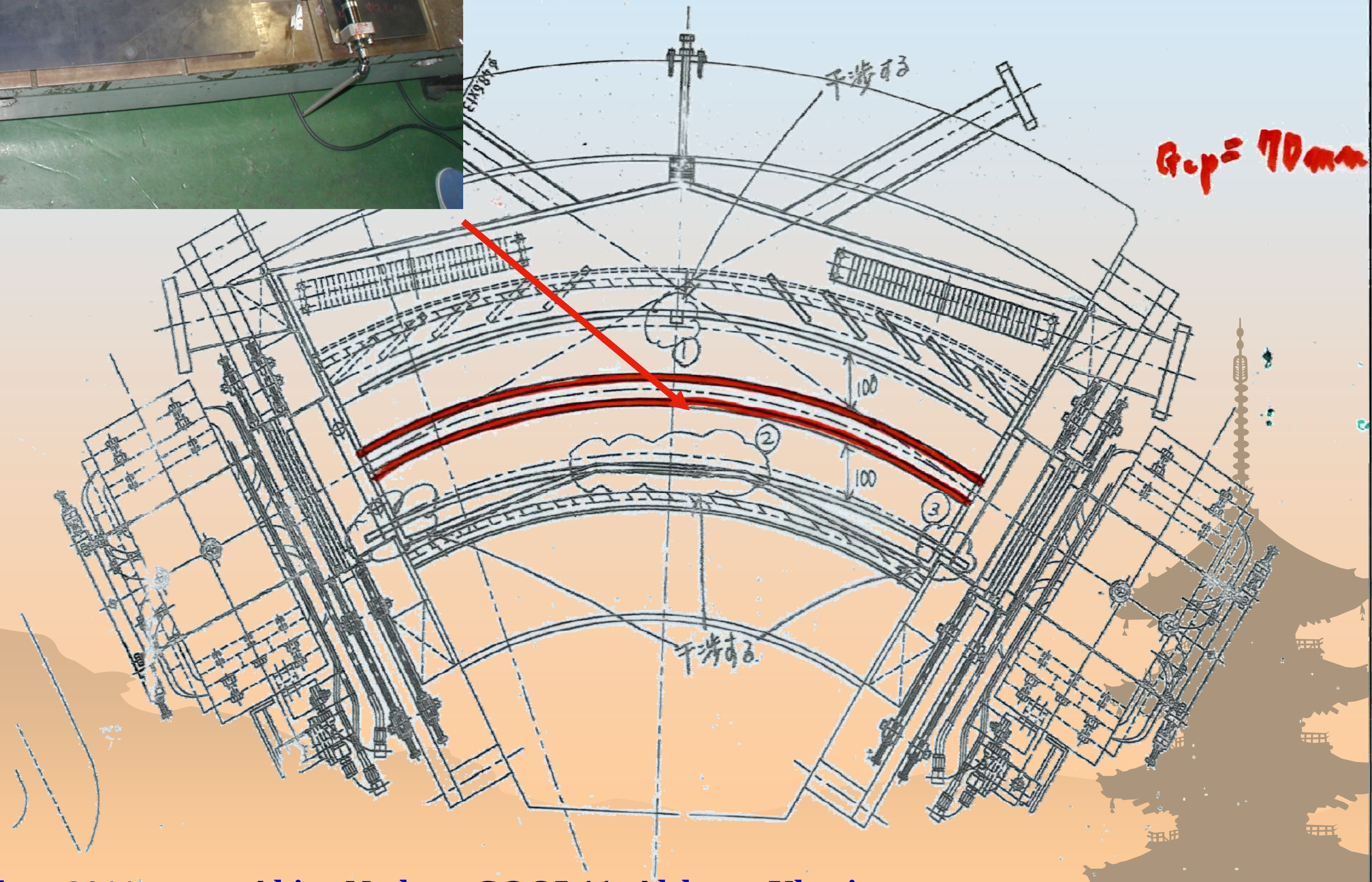
$$\frac{\Delta W}{W} = 2\frac{\Delta P}{P}$$

Non-relativistic Case

↓

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

Vacuum Chamber in the Magnet Section (includes the Electrodes)



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M Grieser, MPI-K, Heidelberg, Germany

Thank you for your kind attention！