Approach to the Low Temperature State oriented for Crystalline Beam

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at

RuPAC 2012

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- 1D Ordering of Proton by Electron Cooling
- Formation of Short Bunch Beam→Vertical Beam Course for Bio-medical Irradiation

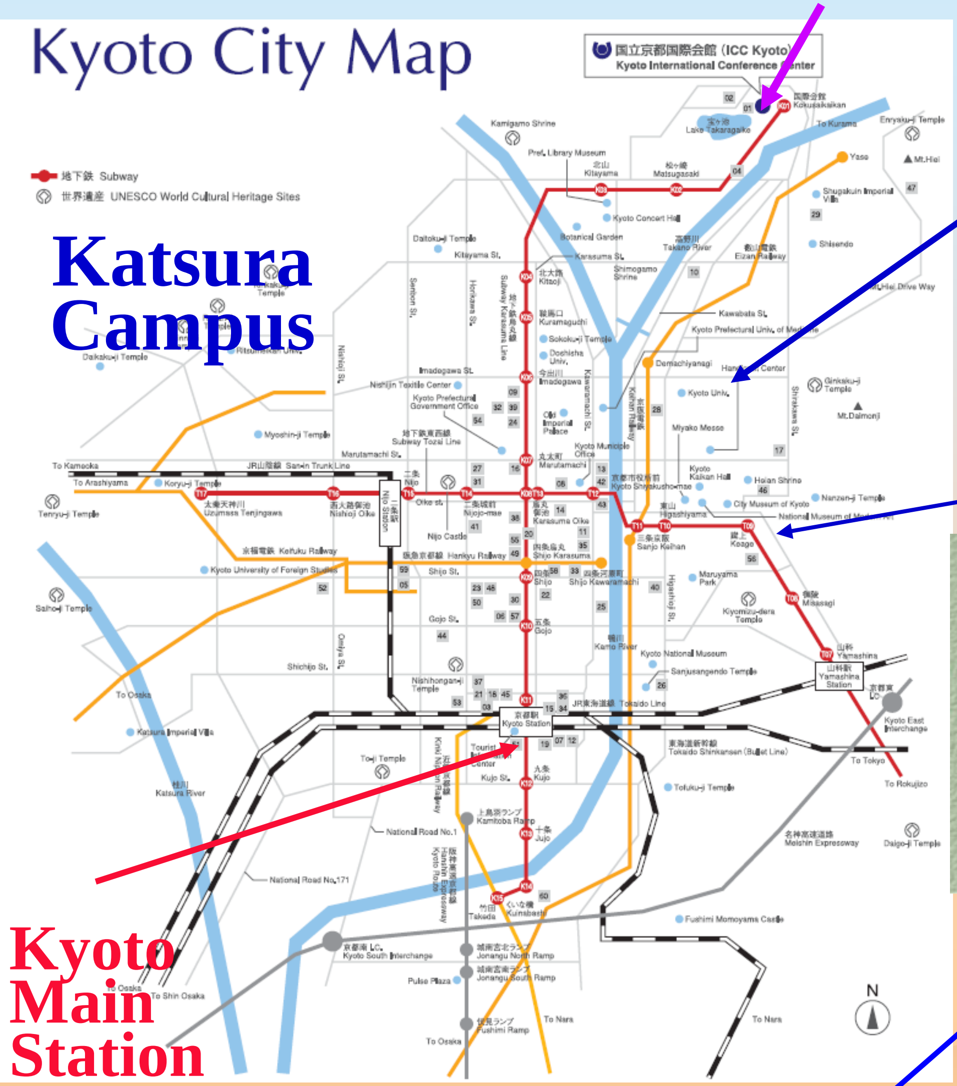
b) Laser Cooling

- Longitudinal Laser Cooling of Coasting Beam
- Indirect Transverse Laser Cooling by SBRC (Synchro-Betatron Resonance Coupling) →Increase of its cooling efficiency by Scraping

3. Perspective for Future Research

Campus of Kyoto University

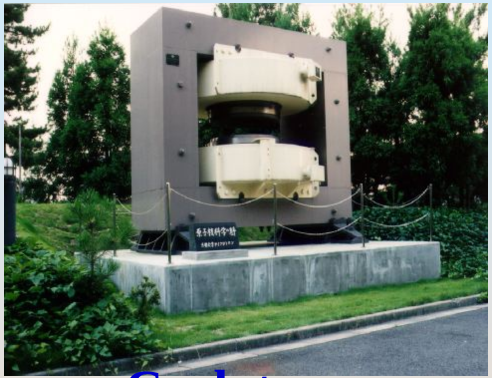
Kyoto International Conference Center used as a site of IPAC'10



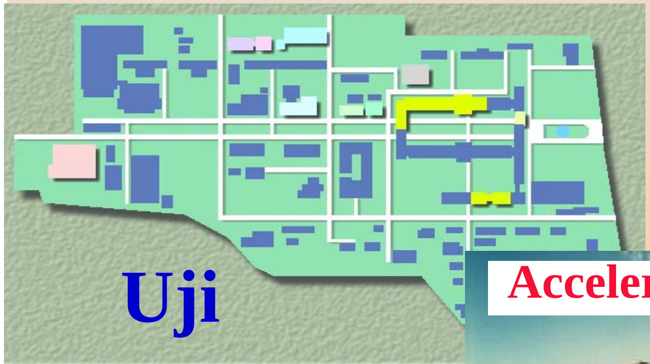
Katsura Campus

Kyoto Main Station

Main Campus



Cyclotron (1955~1985)



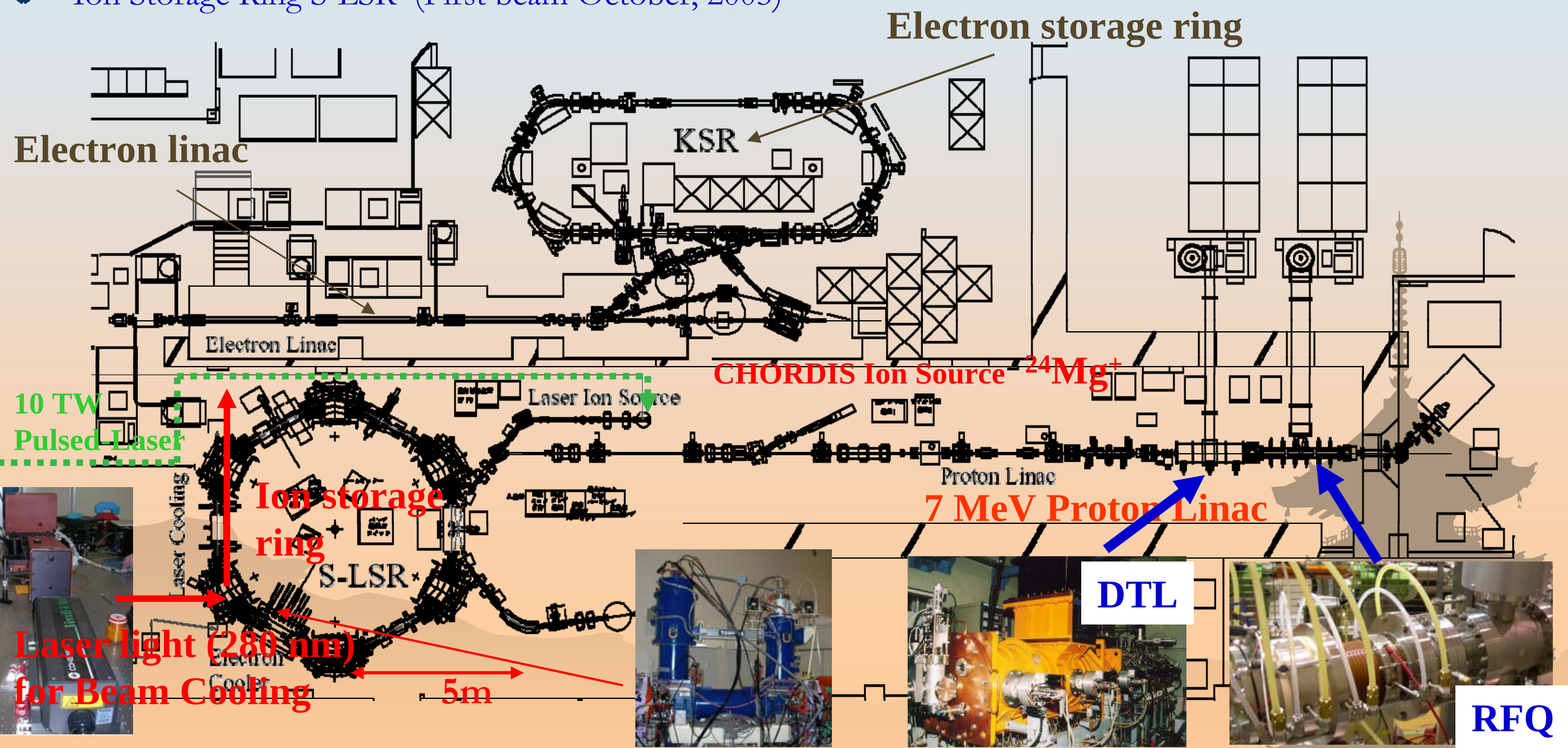
Uji Campus

Accelerator Building

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)

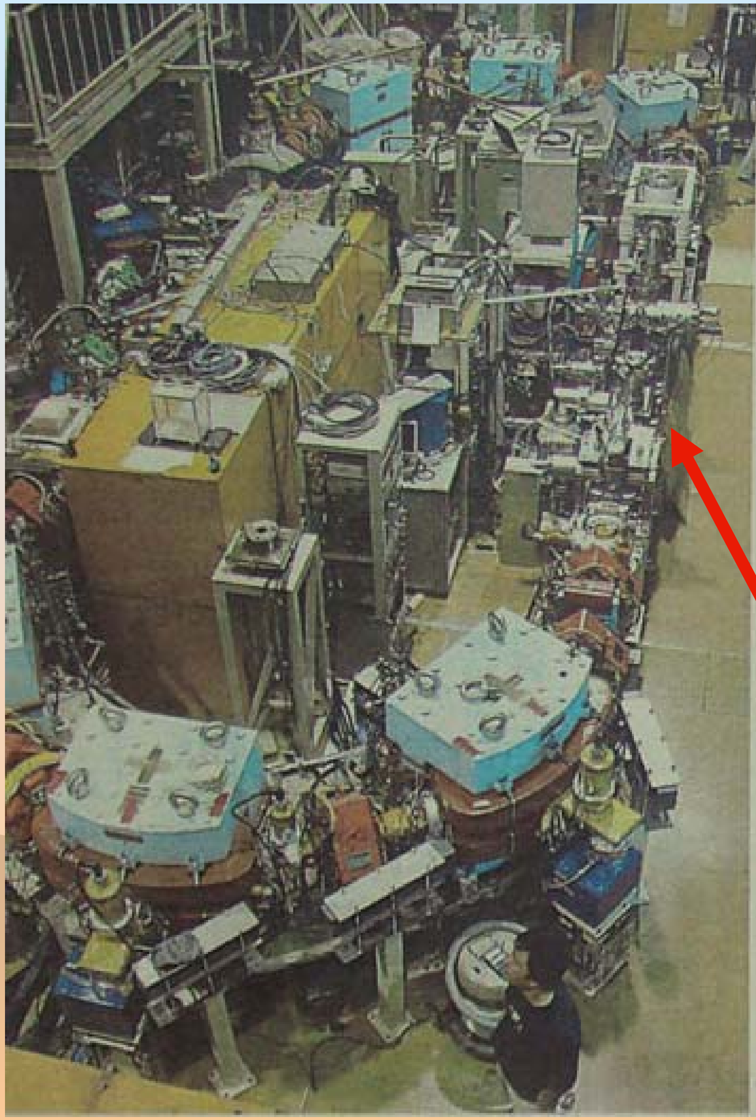
- Electron Cooler (existing)
- $^{24}Mg^{+}$ Ion Source 40 keV (existing)
- Laser Cooling for $^{24}Mg^{+}$ (existing-still under development)

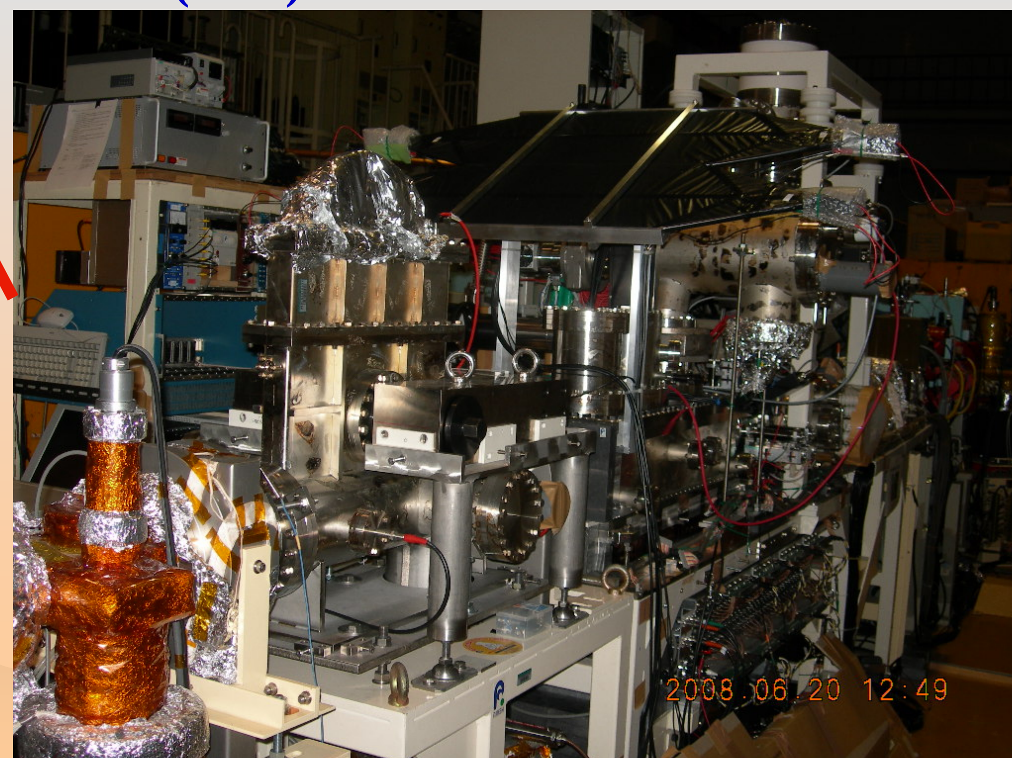


SCRIT Installed into S-LSR

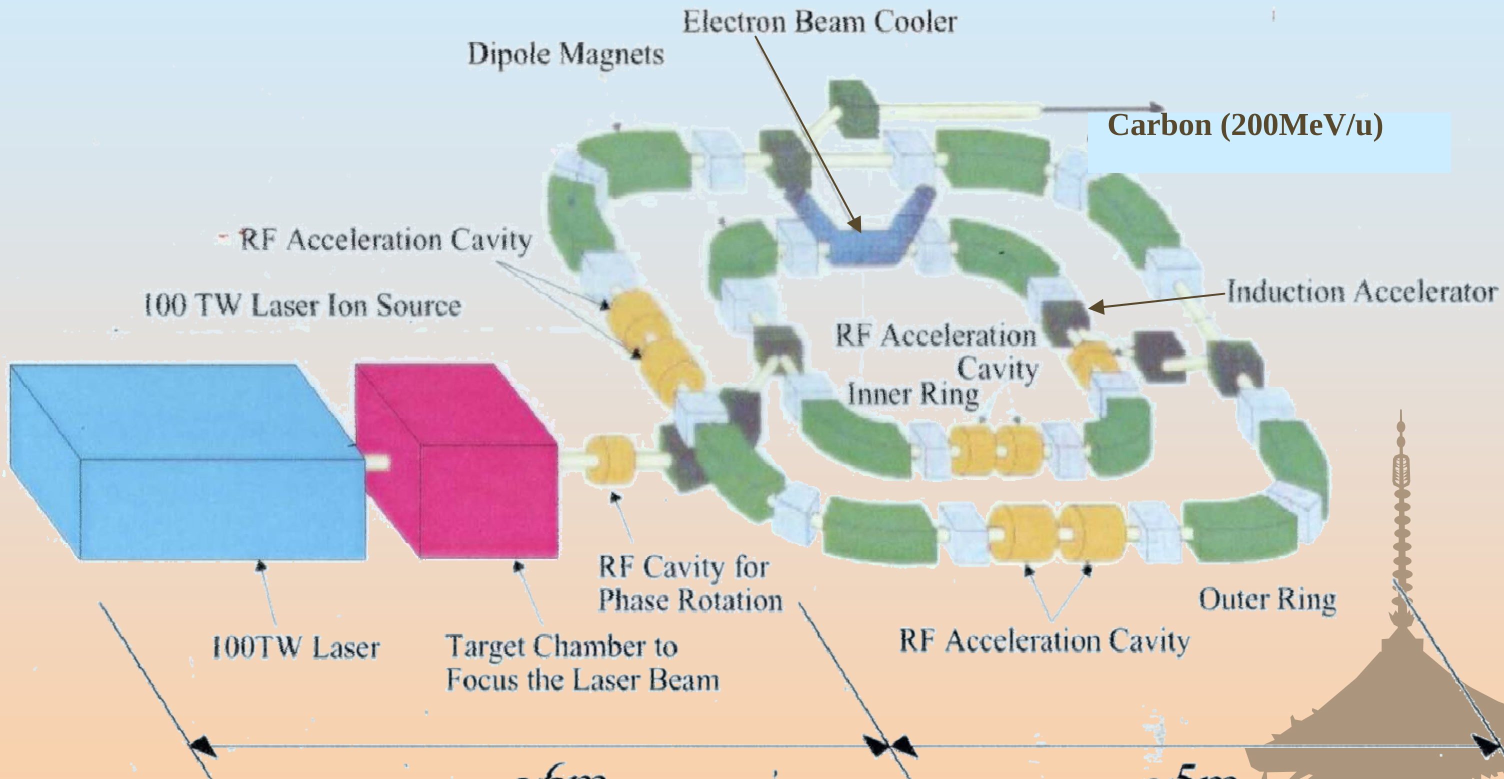
SCRIT(self-confining radio active isotope ion target)
An "ion trapping" phenomenon in the electron storage ring was successfully utilized for the first time to form the target for electron scattering.

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





Downsizing is possible by combination of Laser Ion Source and High Magnetic Field Pulse Synchrotron



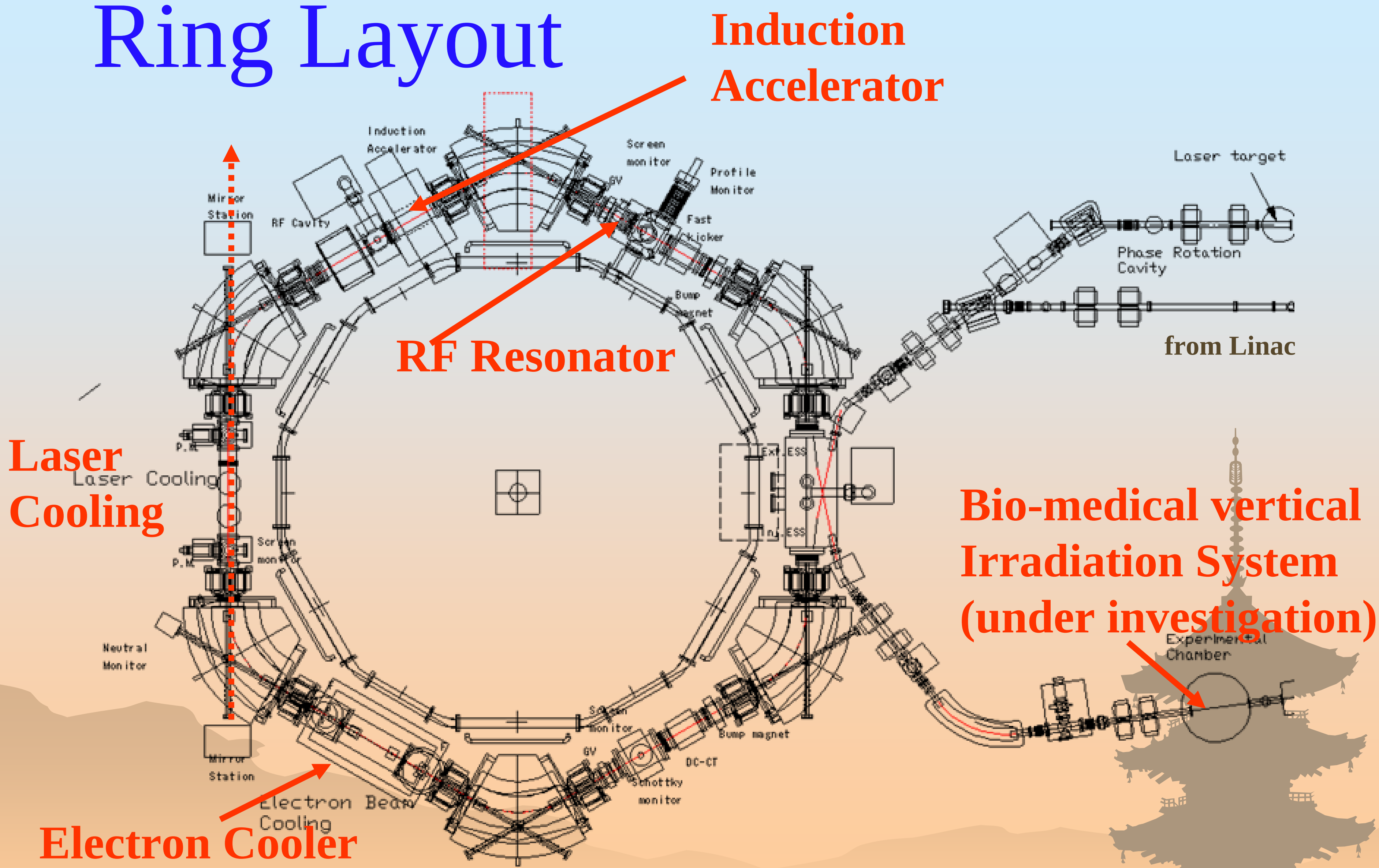
Compact Heavy-Ion (Carbon Ion) Synchrotron

Our Research at S-LSR on Beam Cooling

- **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 Resonance Coupling" (SBRC)

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
Fast kicker
Bump magnet
RF Cavity
Mirror Station
Laser Cooling
Laser target
Phase Rotation Cavity
Neutral Monitor
Electron Beam Cooling
Schottky monitor
DC-CT
Bump magnet
Experimental Chamber

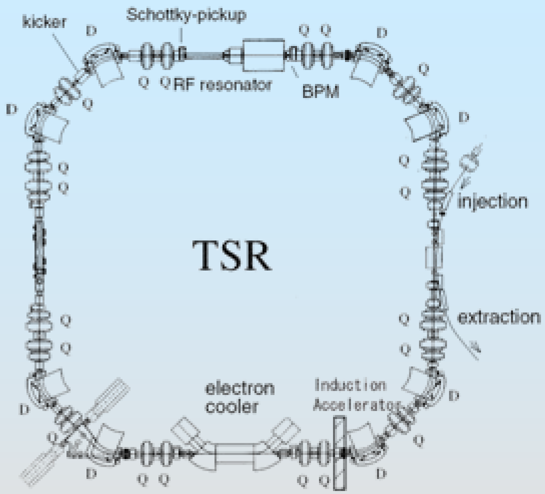
Main Parameters of S-LSR

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( )**
	2.072 (H), 1.115 (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

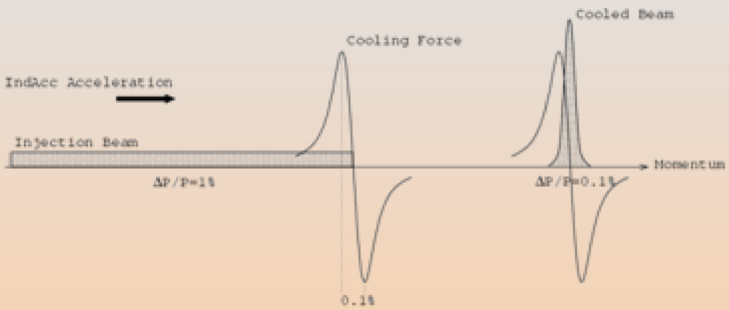
Electron Cooling of Hot Carbon Beam at TSR

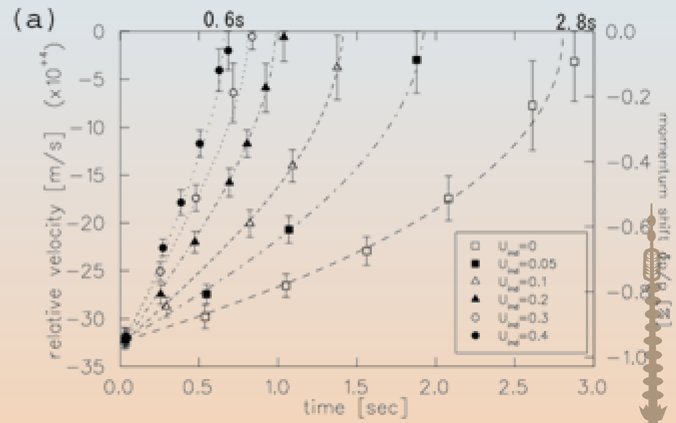
by H. Fadil



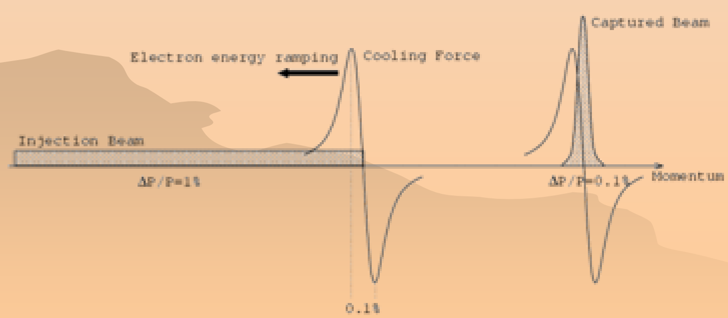
TSR Experiment parameters	
Ion species	C^{6+} 73.3 [MeV]
Electron density	2.4×10^{7} [cm^{-3}]
cooler length	1.2 [m]
Magnetic field	300 [G]
Induction voltage	0 ~ 0.4 [V]

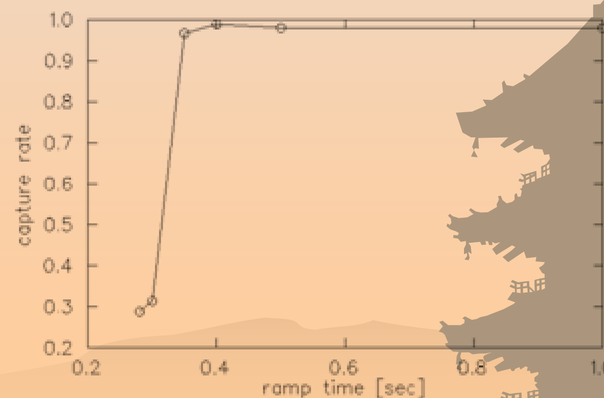
Ion beam energy sweeping scheme





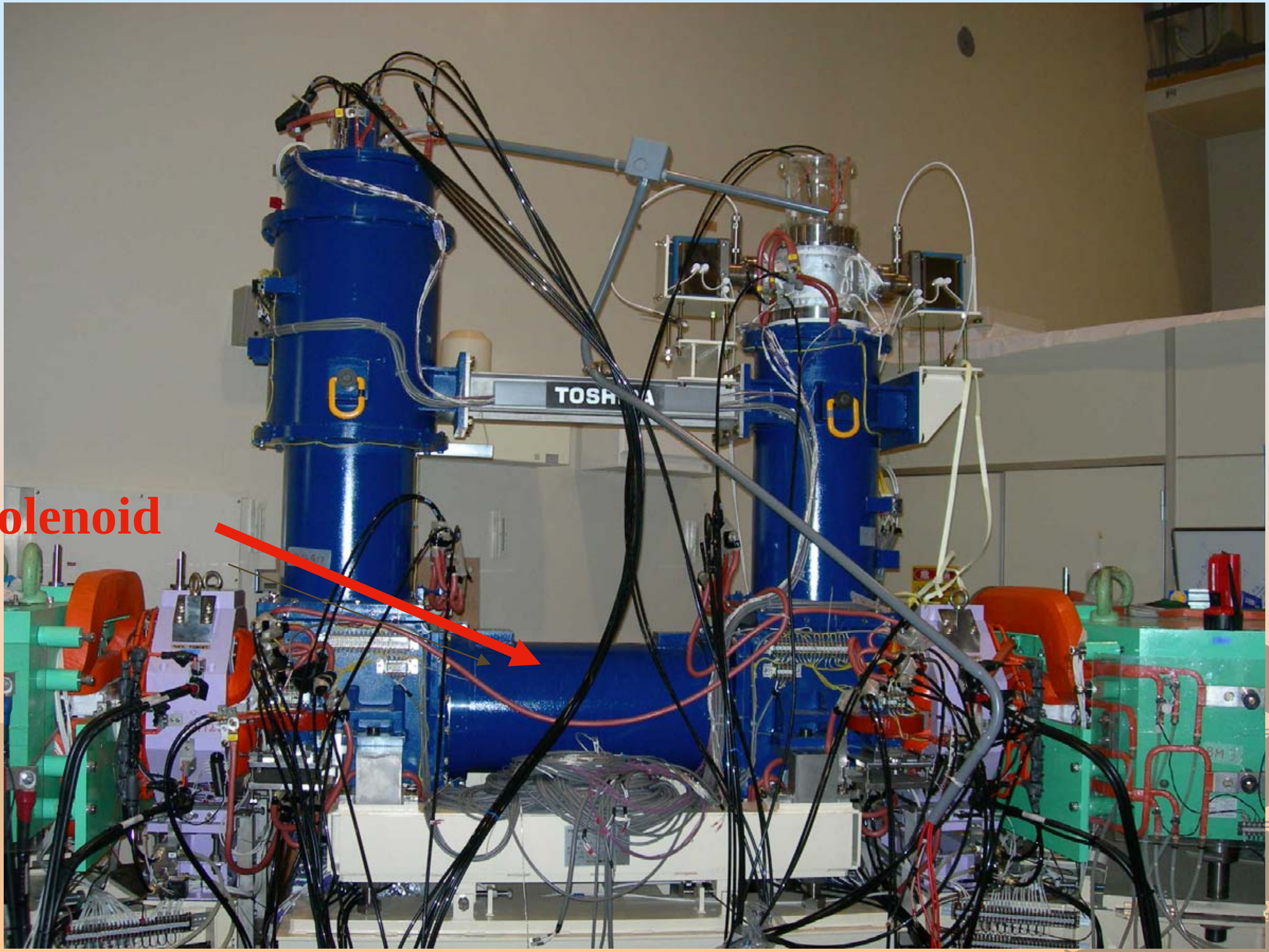
Electron beam energy sweeping scheme



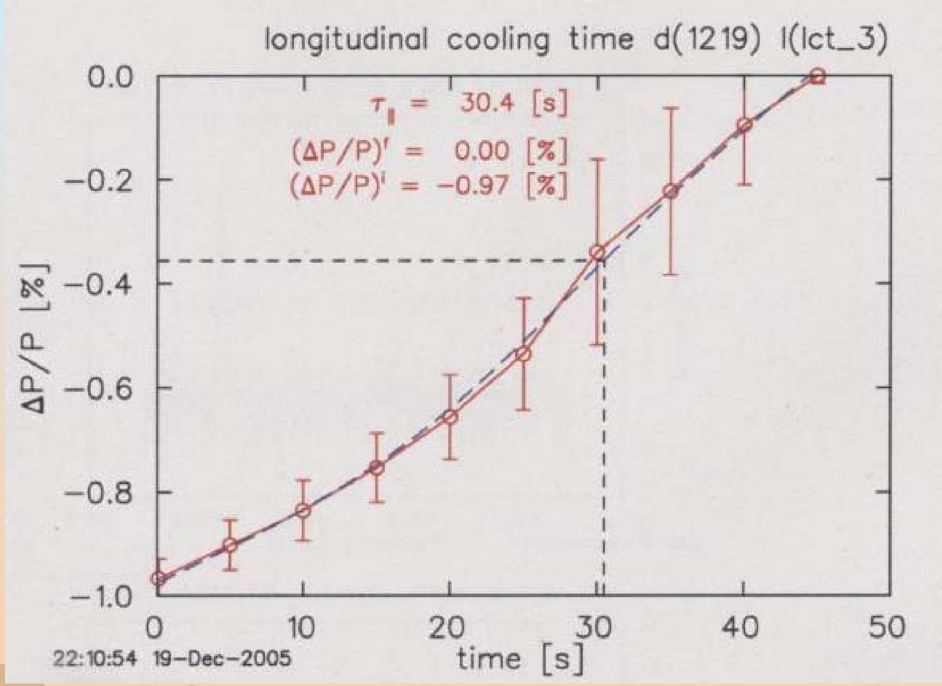


Electron Cooler installed in S-LSR

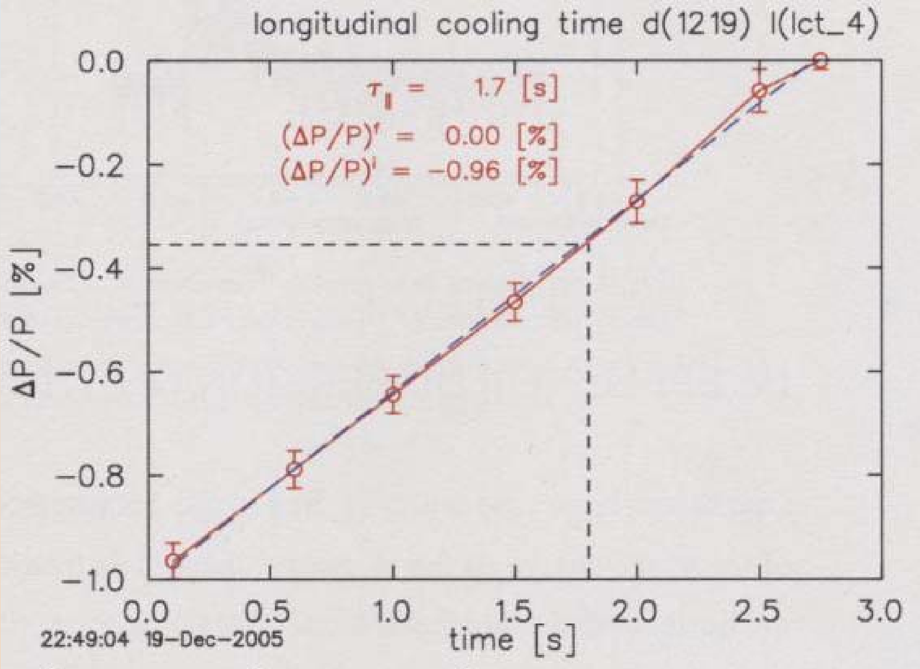
Cooler Solenoid



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

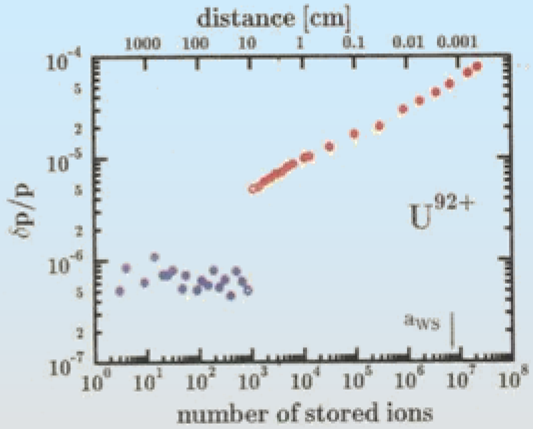


Figure 2. Experimental momentum spreads from Schottky signals vs. number of stored ions in the ESR for electron cooled U^{92+} ions at 240 MeV/u. a_{WS} indicates the Wigner-Seitz radius of eq.(3). (after ref. [9])

CRYRING at Stockholm, by H. Danared

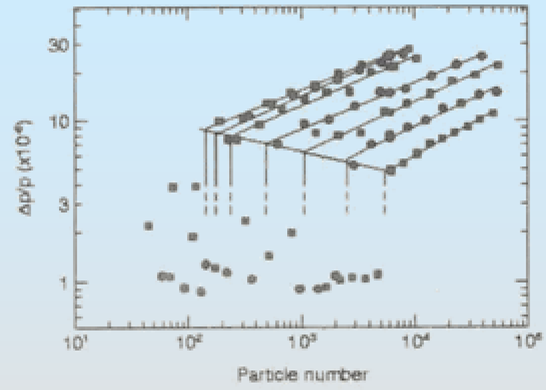


Fig. 5: Relative momentum spread as a function of particle number for the lowest seven electron densities represented in Fig. 2. The density increases from the upper left to the lower right. For each density, a line is fitted to the data points. A line is also drawn through the points corresponding to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

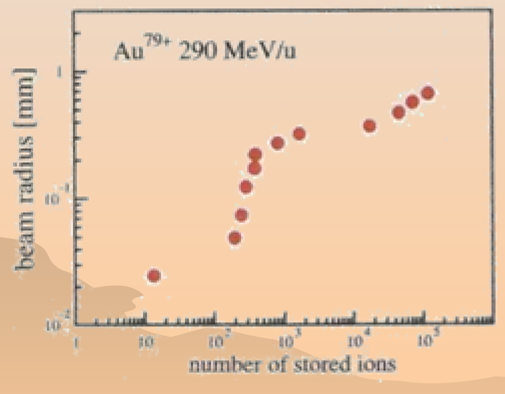


Figure 3. Beam radius measured with a beam scraper vs. number of stored ions in the ESR for electron cooled Au^{79+} ions at 290 MeV/u (from ref. [10]).

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

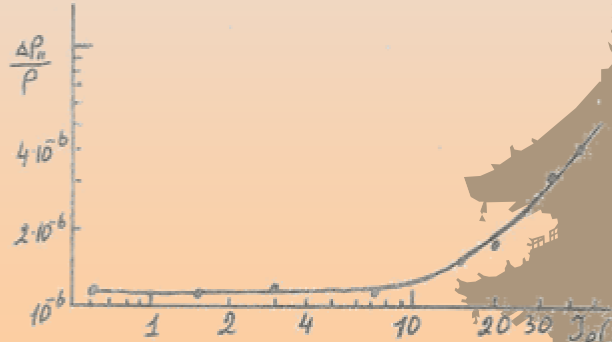
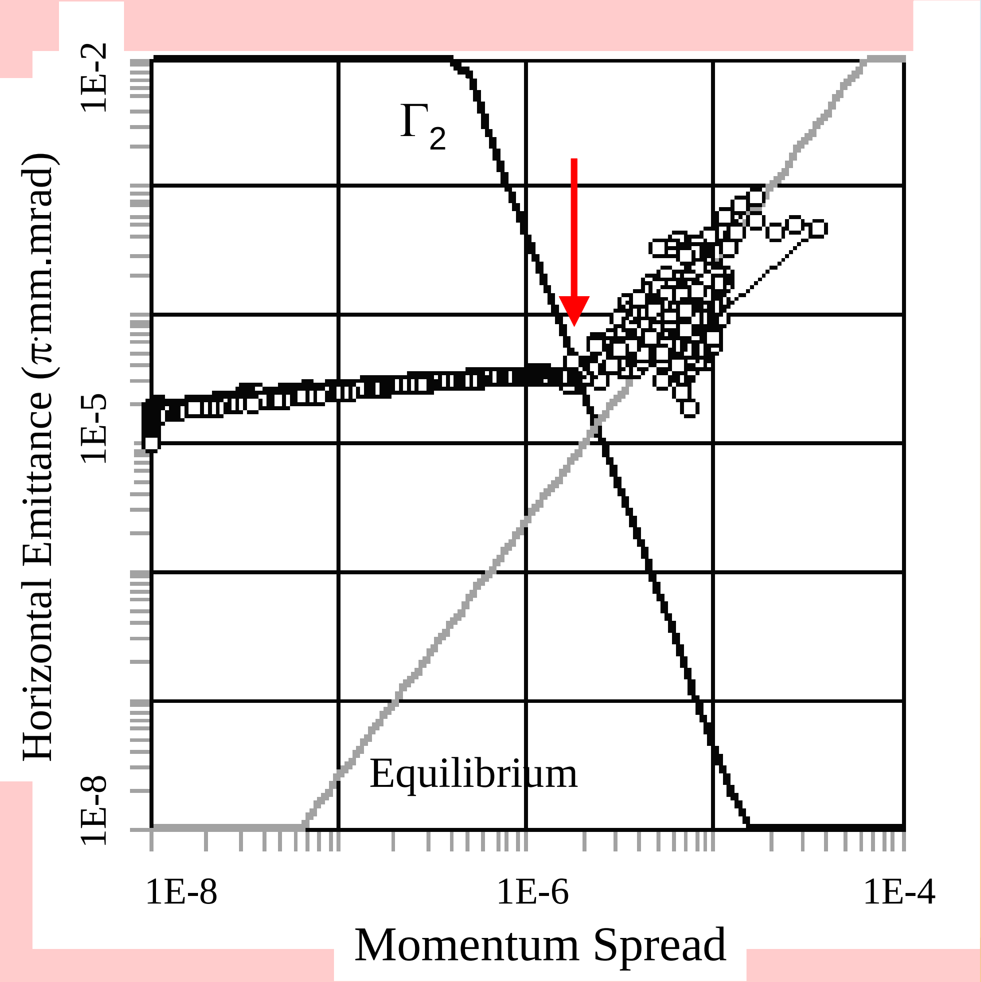


Fig. 6. The momentum spread of proton beam versus current J_p.

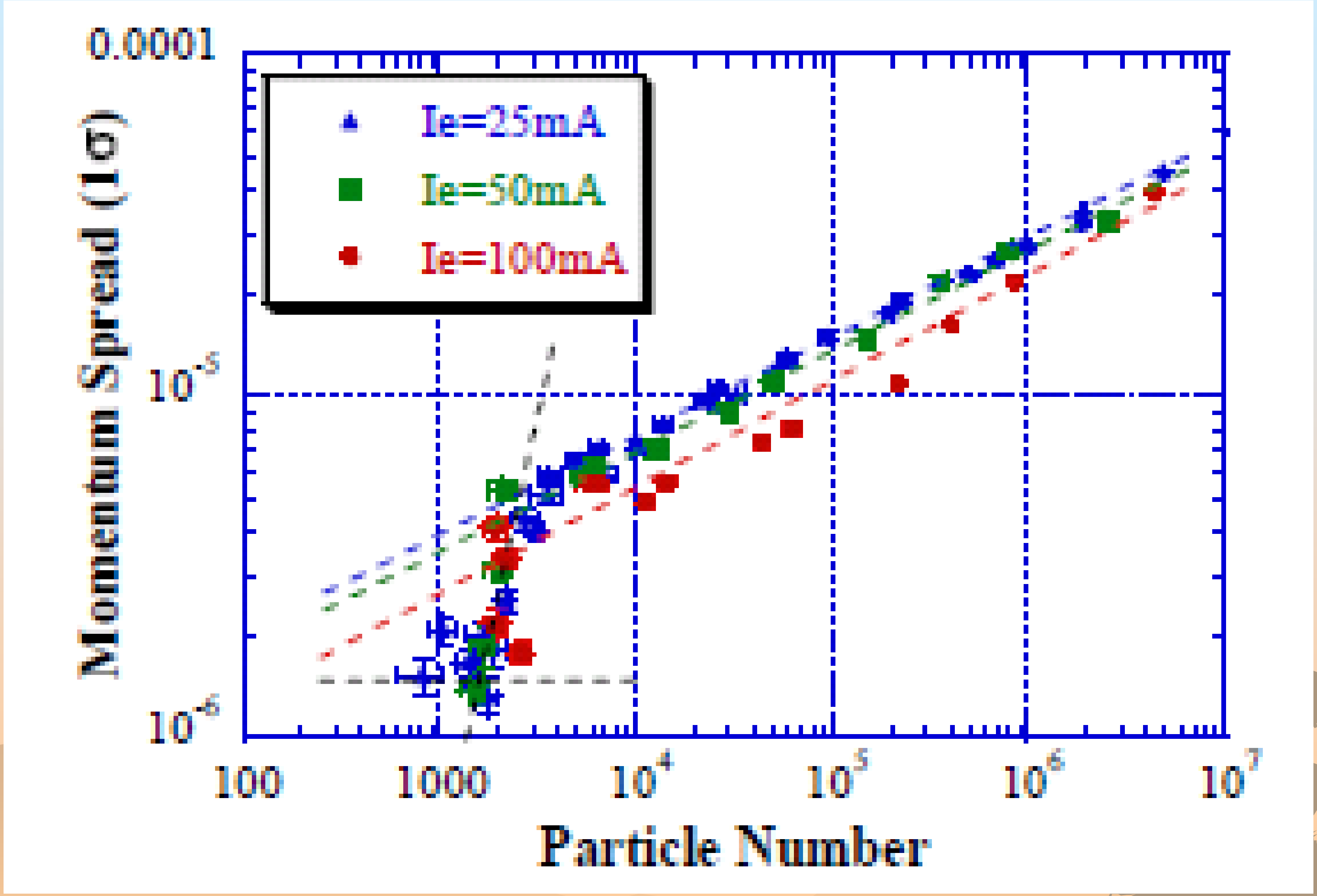
Simulation with Betacool predicts
1D ordering of 7 MeV proton at S-LSR
-particle number of 3000-



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

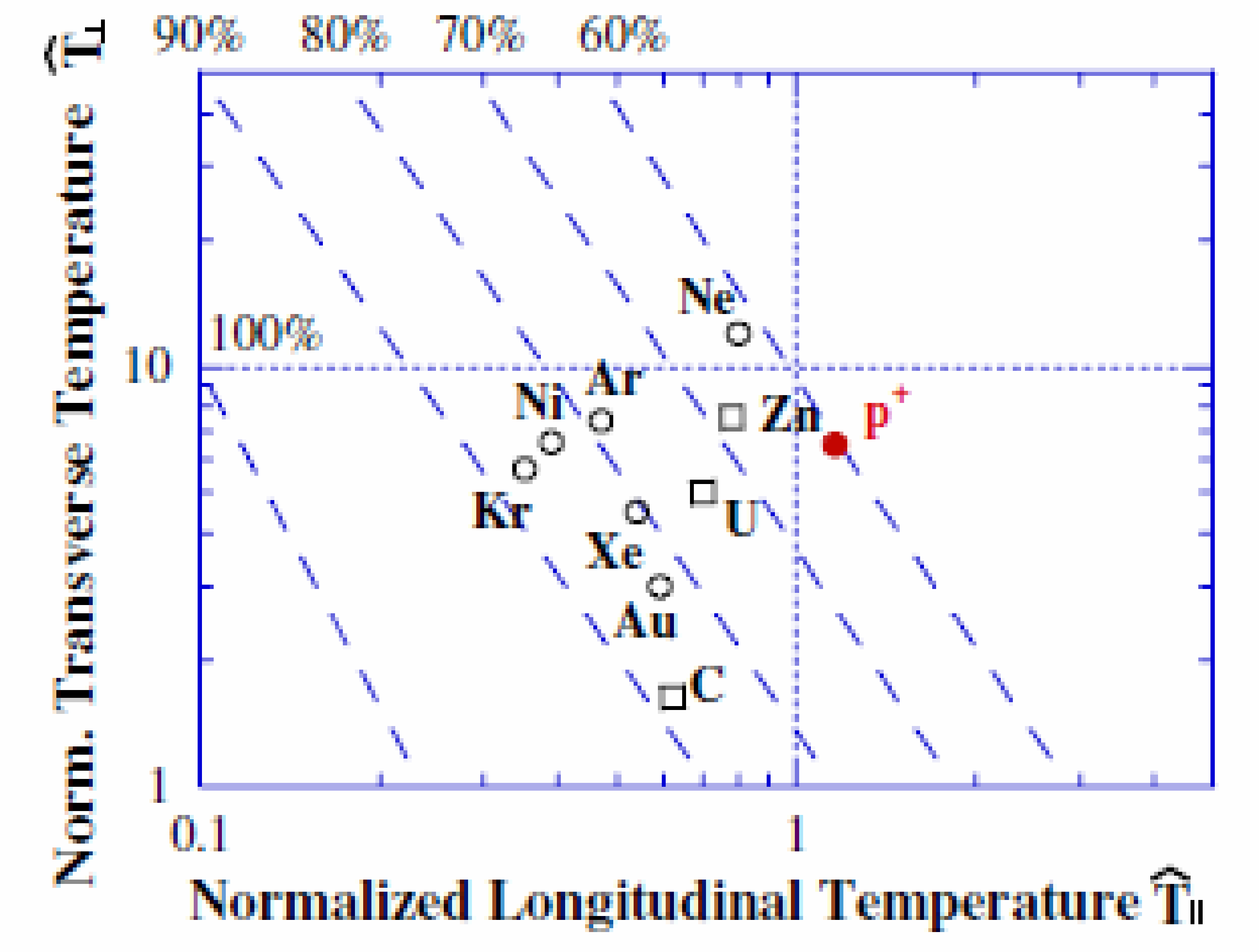
Collaboration with JINR, Dubna by Prof. I. Meshkov and Dr. A. Smirnov et al.

Phase Transition to 1D Ordered State



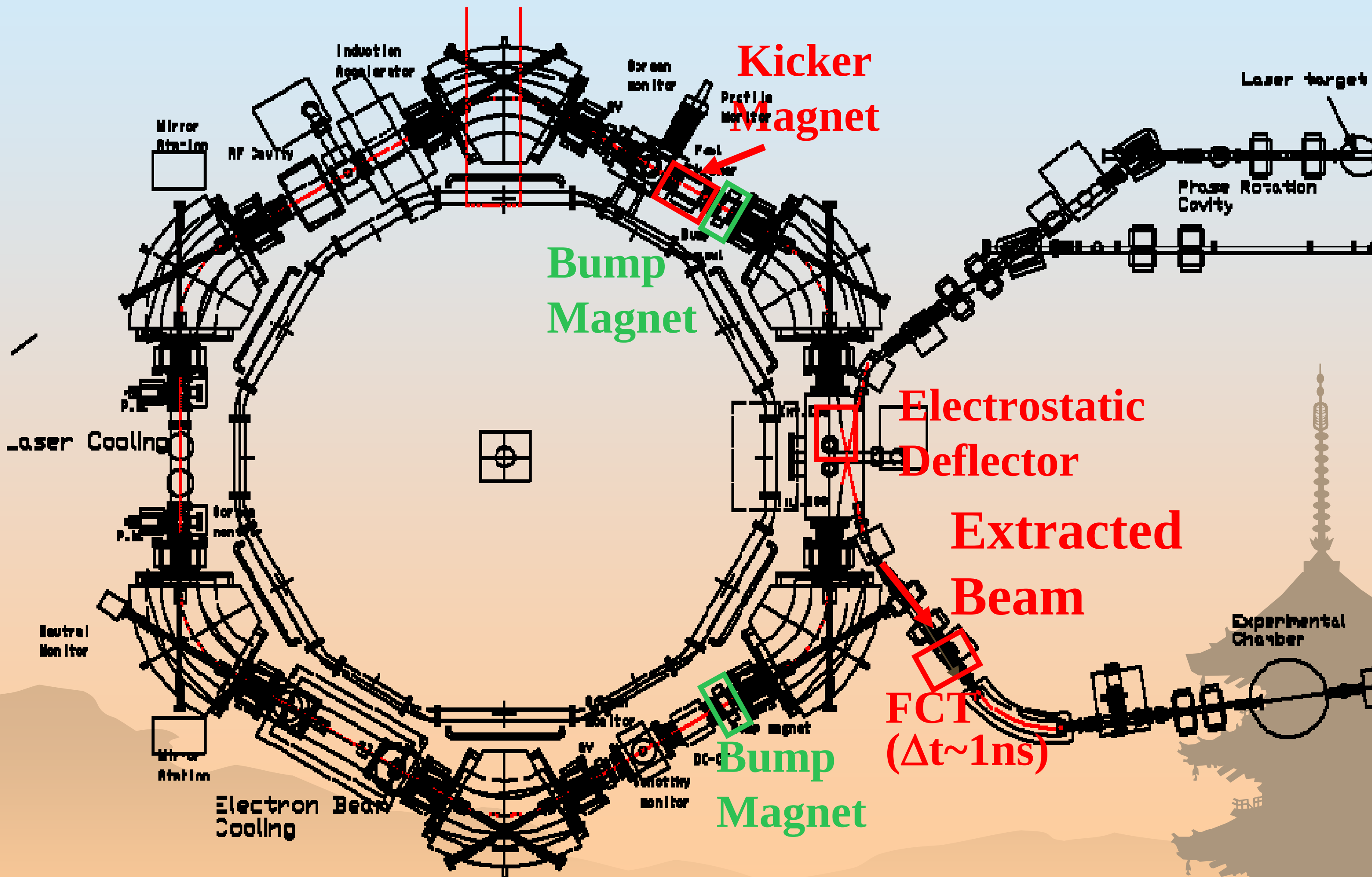
T. Shirai et al., PRL, 98 (2007) 204801

Reflection Probability of Ions made Phase Transition

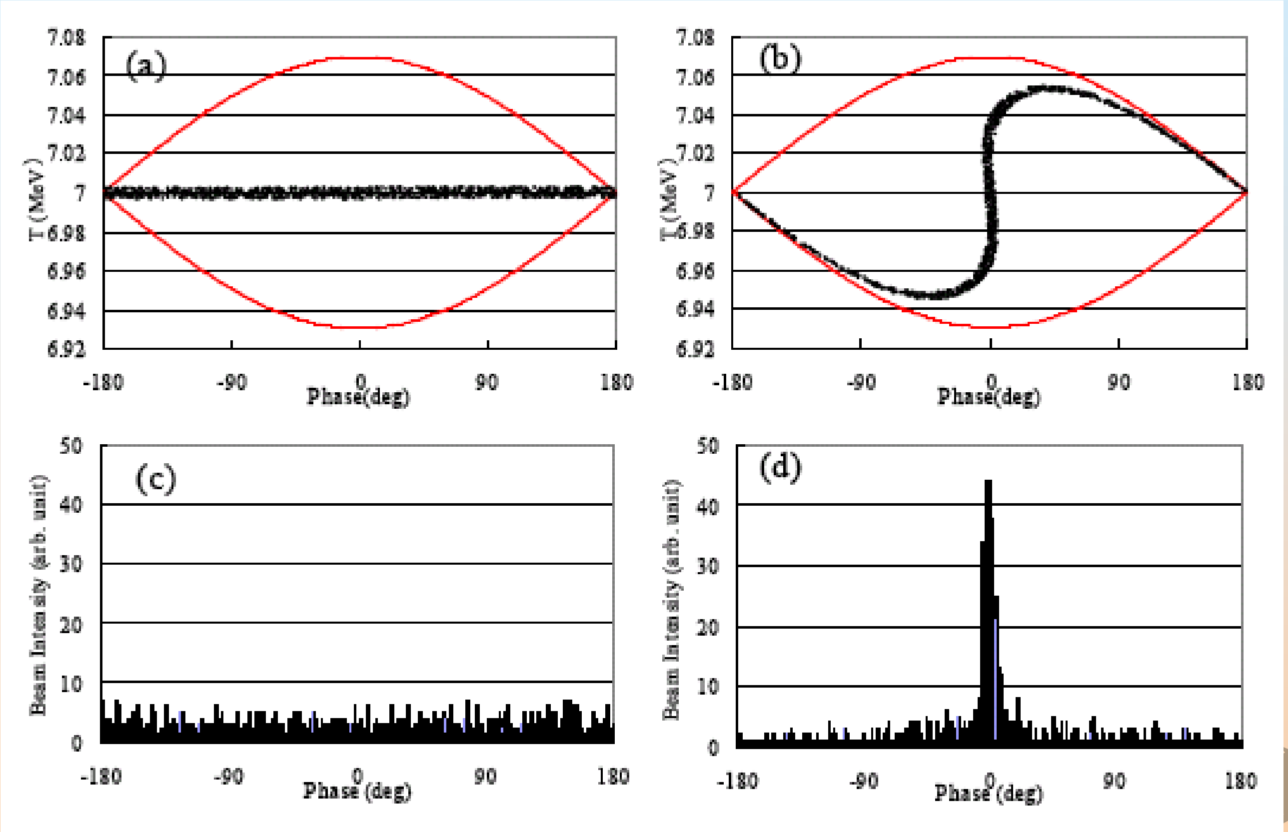


- **Creation of Ultra-short Bunch Beam and its fast extraction →Verical Irradiation System**

Fast Extraction System at S-LSR

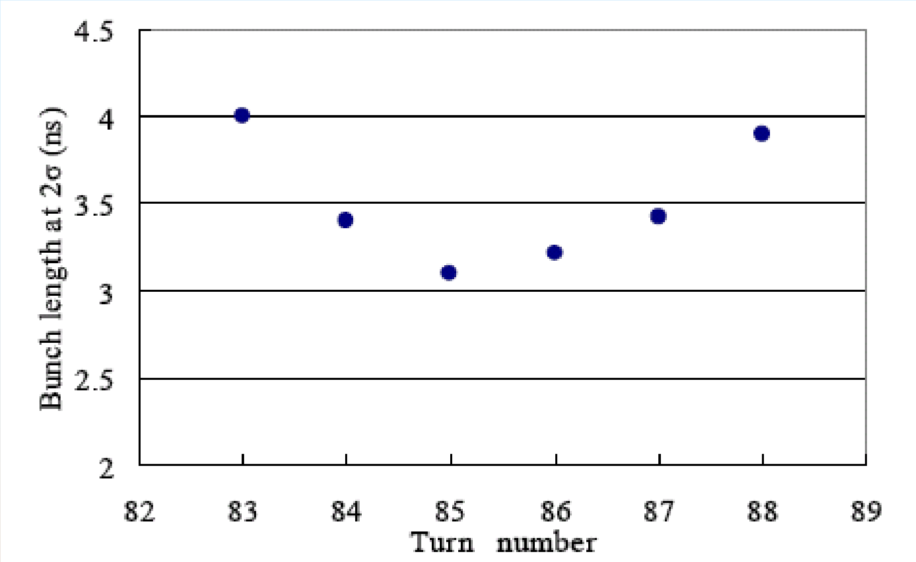


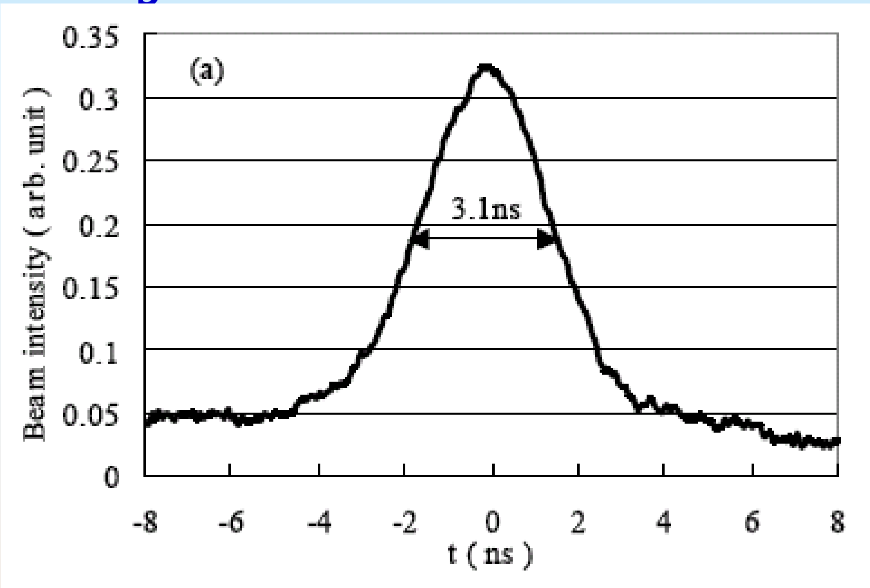
Bunch Rotation of 7 MeV Proton

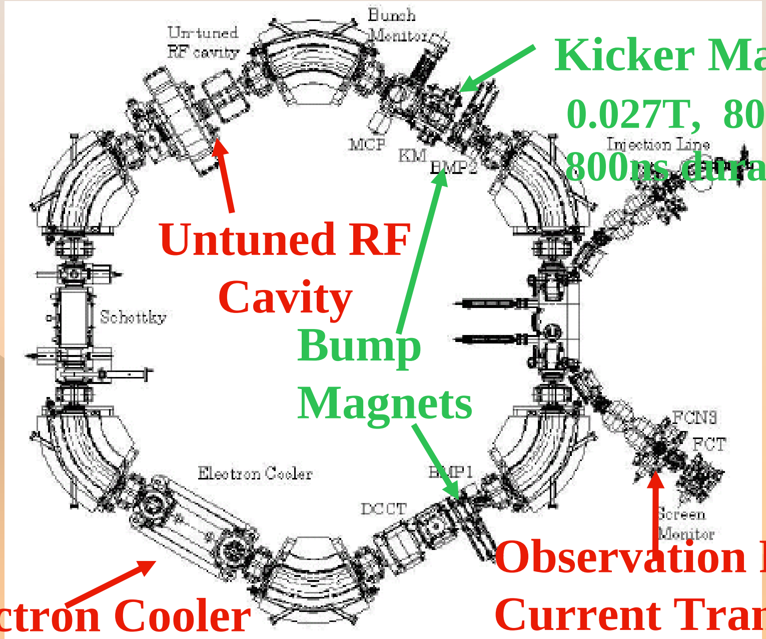


RF field (800 V) is applied to coasting beam after electron cooling and is extracted when the beam is rotated ~90°.

Shortest Pulse Created by Phase Rotation





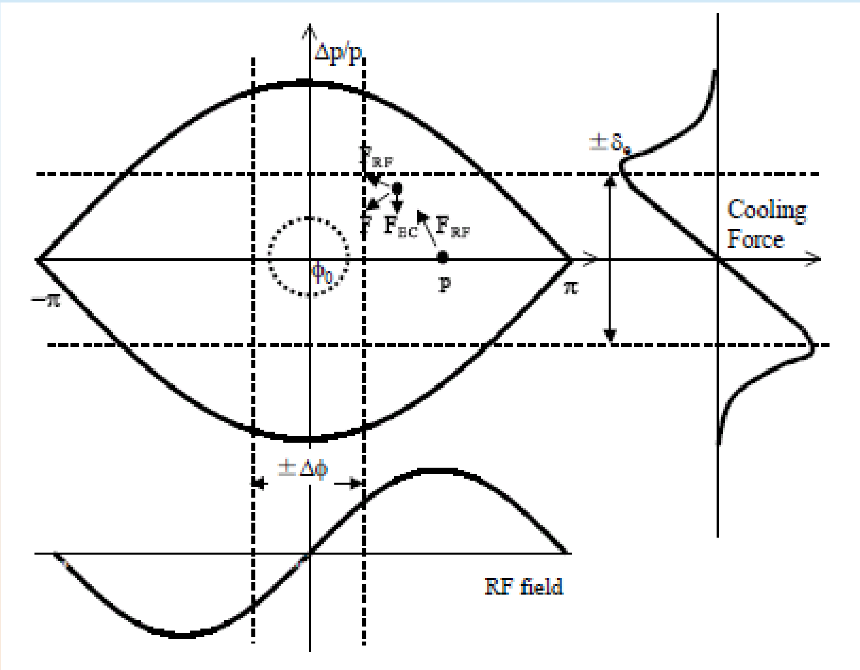


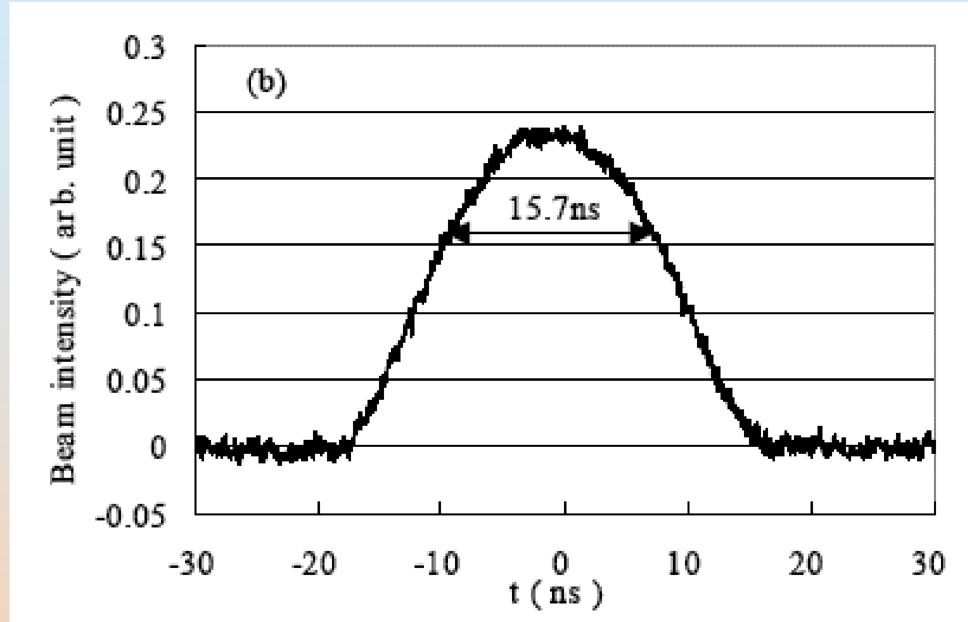
Short bunch duration of 3.1 ns (2σ)
7 MeV proton with Intensity 1.4x 10^8

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%.

DNA Double Strand Break by Laser-produced Proton beam

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

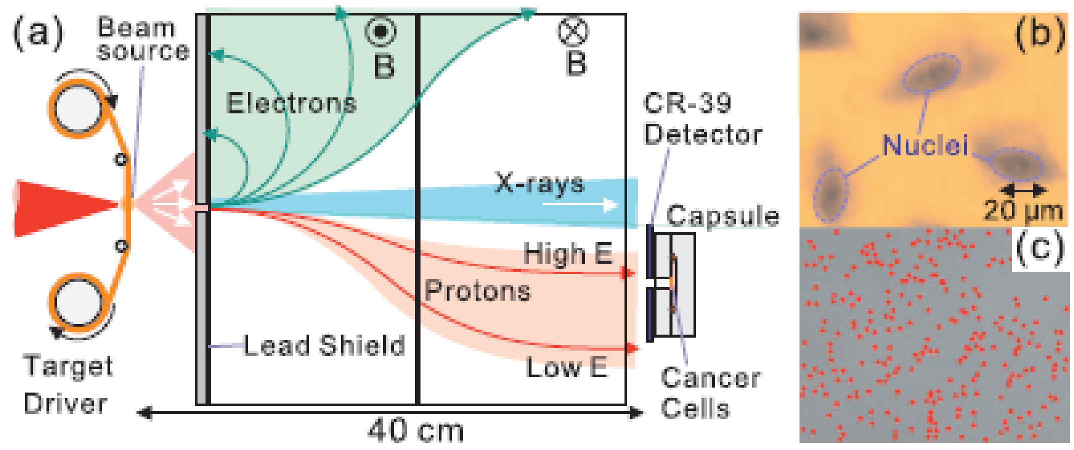


FIG. 1. (Color) (a) A schematic drawing of experimental setup. (b) An image of cancer cells taken by a microscope. (c) A spatial distribution of protons detected by CR-39 in a single laser shot. Each red point represents a single proton bombardment. The screen size is set to be same as that in the frame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

Pulse Width 15ns, 20 Gy

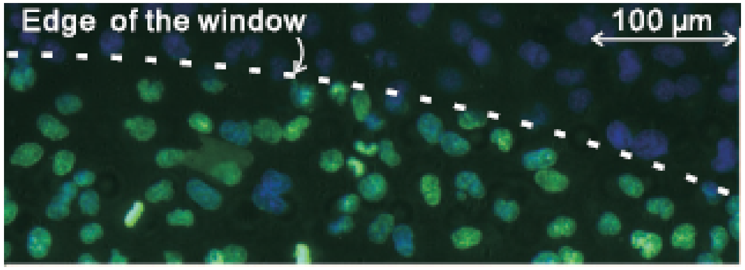
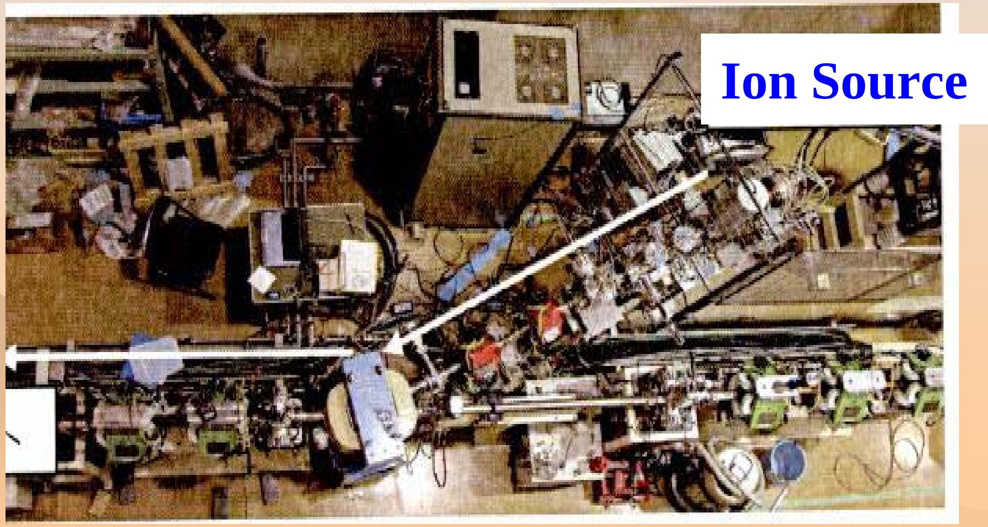
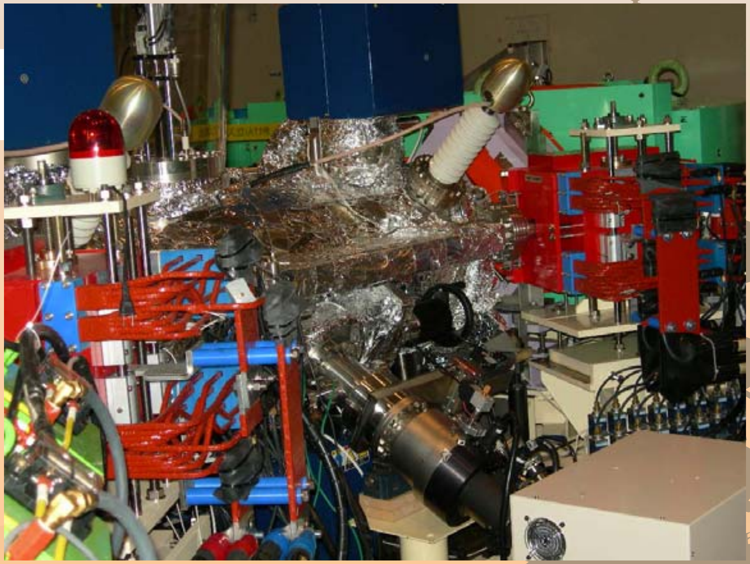


FIG. 3. (Color) γ-H2AX focus formation induced by irradiation of laser-accelerated protons with 20 Gy. γ-H2AX and nucleus are stained with anti-γ-H2AX antibody (green) and DAPI (blue).

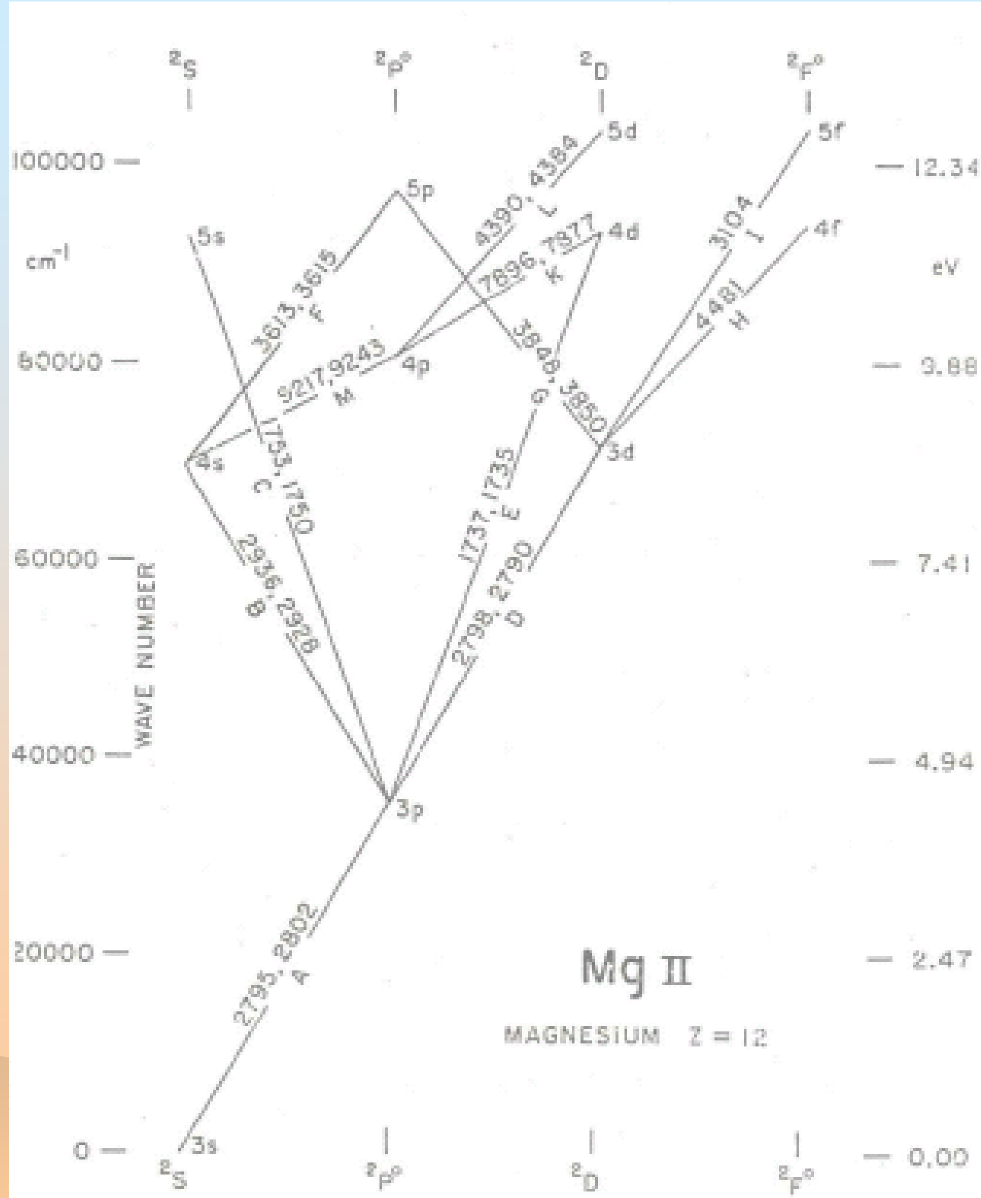
- **Laser Cooling of $^{24}Mg^{+}$ Ion Beam**

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

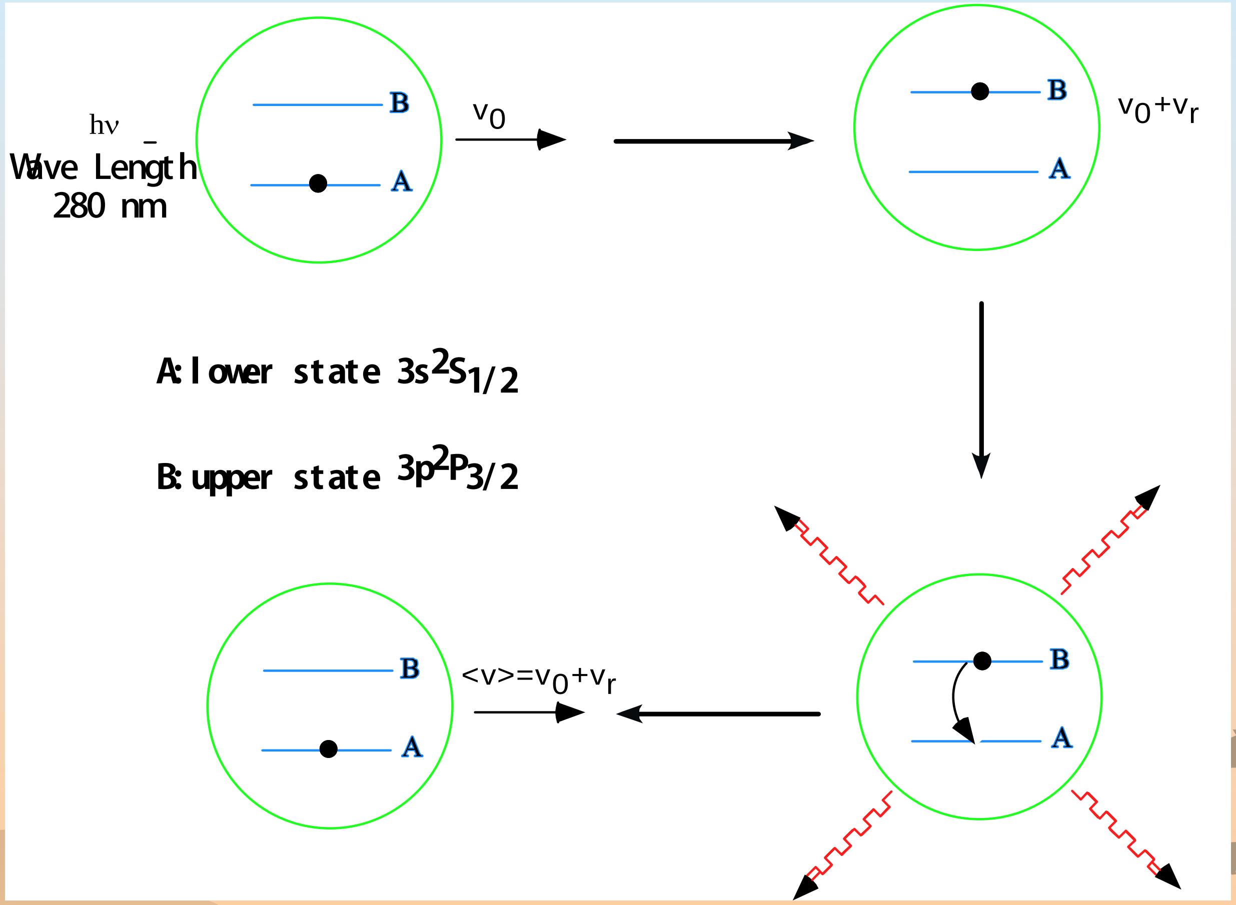




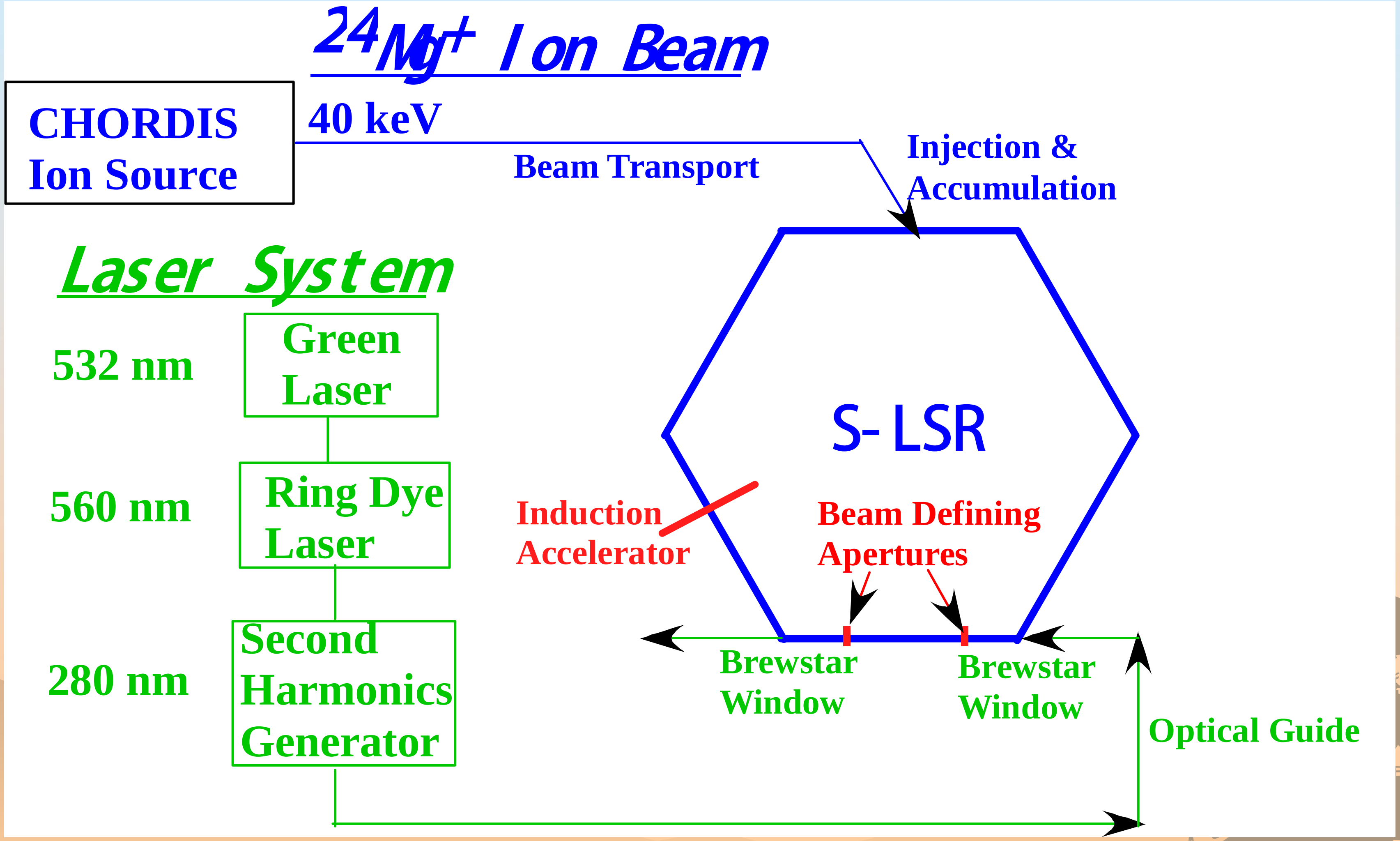
Excited States of Mg Ion



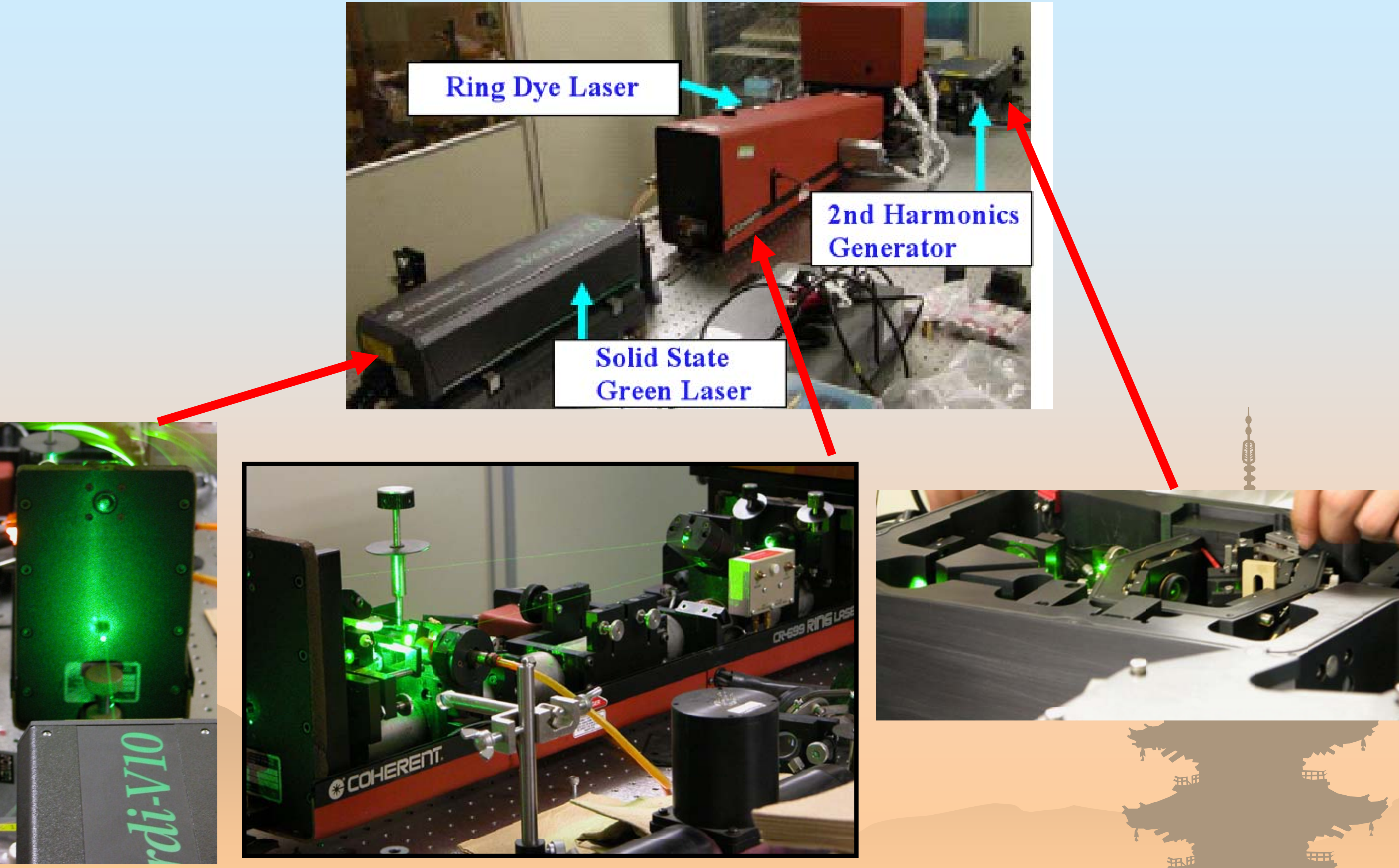
Principle of Laser Cooling (Longitudinal)



Block Diagram of Laser Cooling at S-LSR



Laser System for Cooling



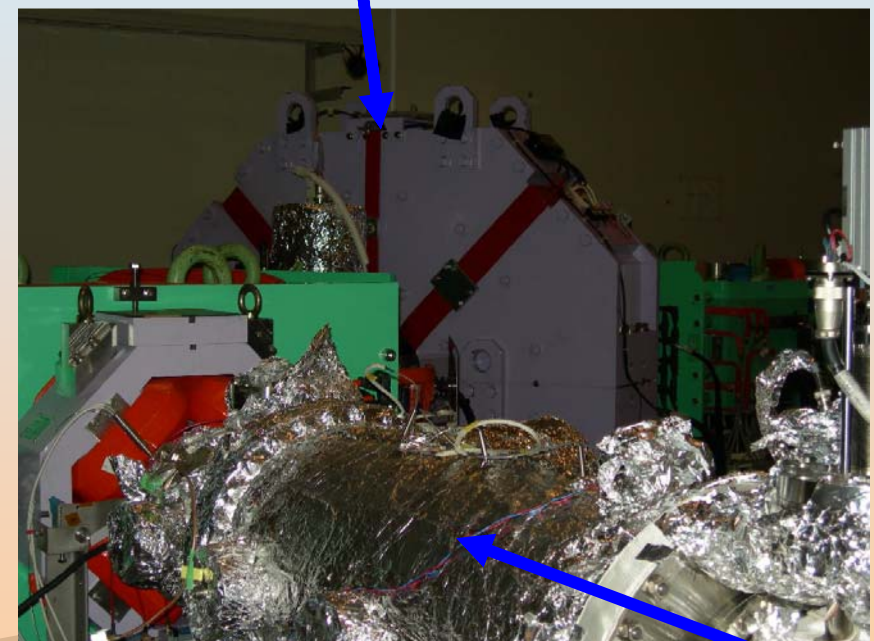
Typical Laser Parameters

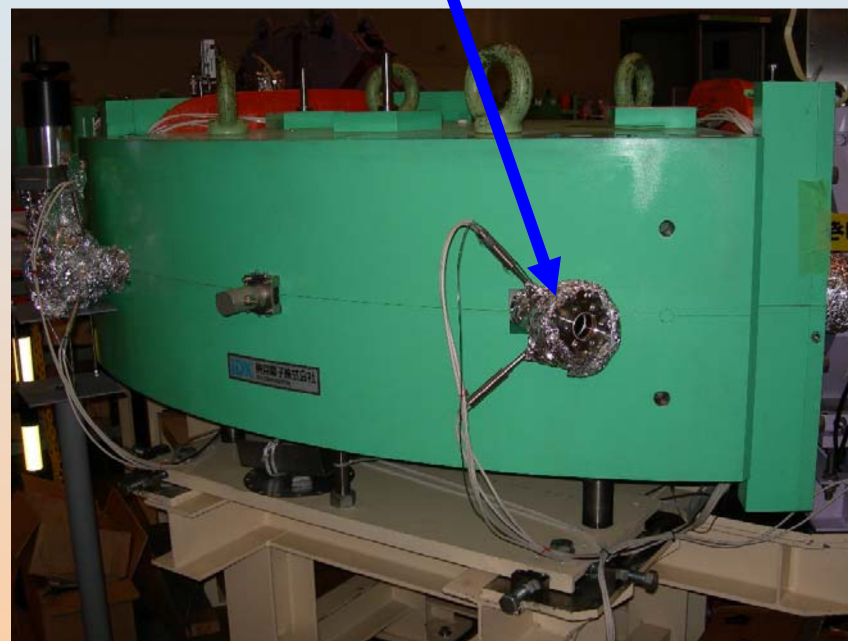
Output of Solid State Laser	8.1 W
Output of Dye Laser	645 mW
Output of Second Harmonics Generator	47 mW
Wavelength	~279 nm
Saturation Intensity	254 mW/cm^2

Laser Cooling Section of S-LSR

Induction Accelerator

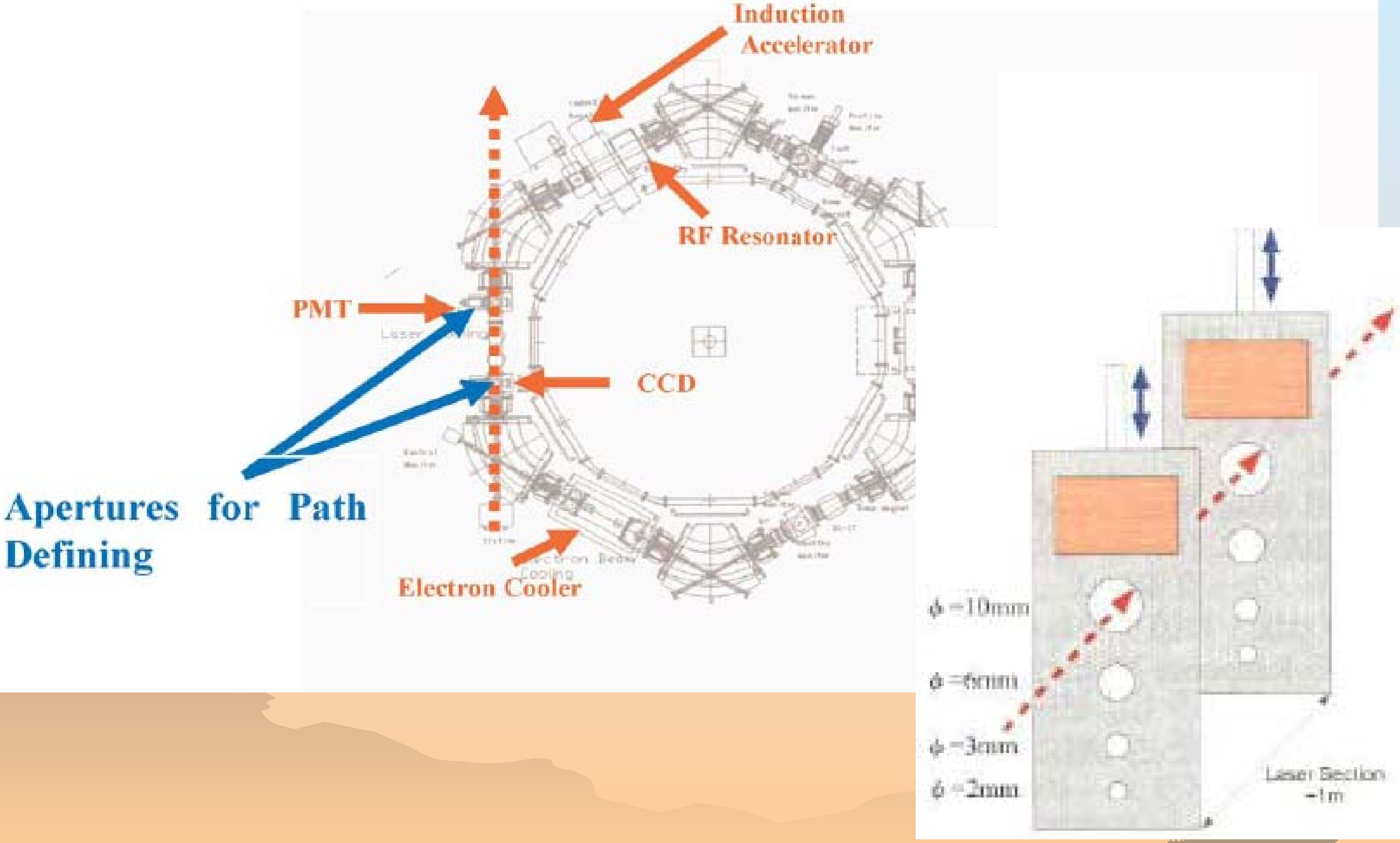
Window for Laser port





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

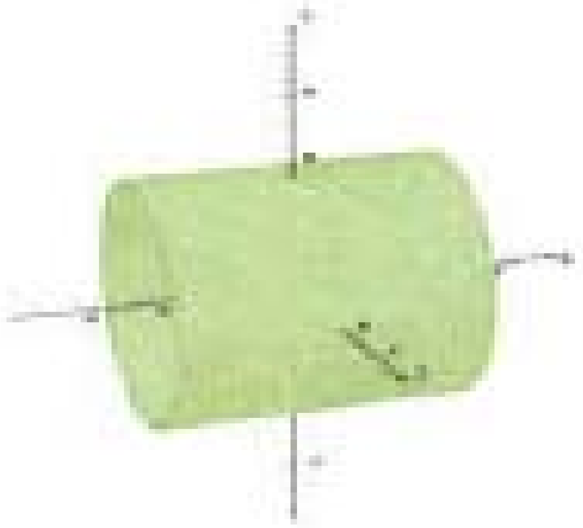
Overlapping of Ion and Laser Beams



By T. Ishikawa

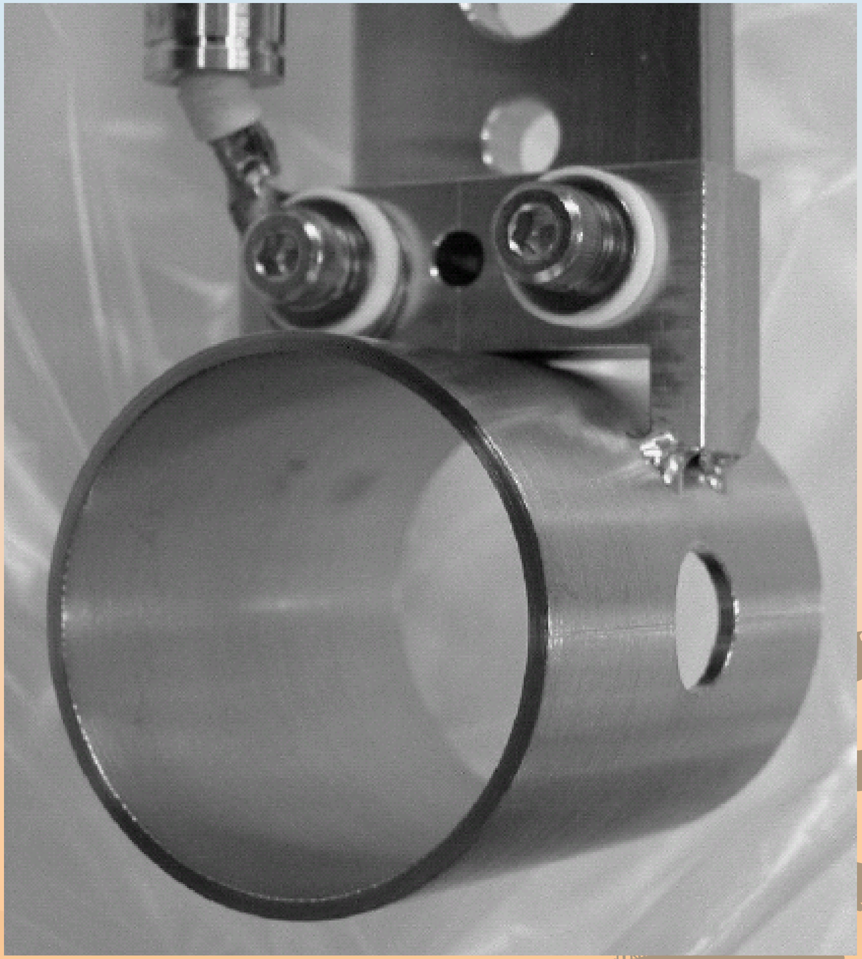
Post Acceleration Tube (PAT)

-Energy Sweep is applied for Distribution Measurement-

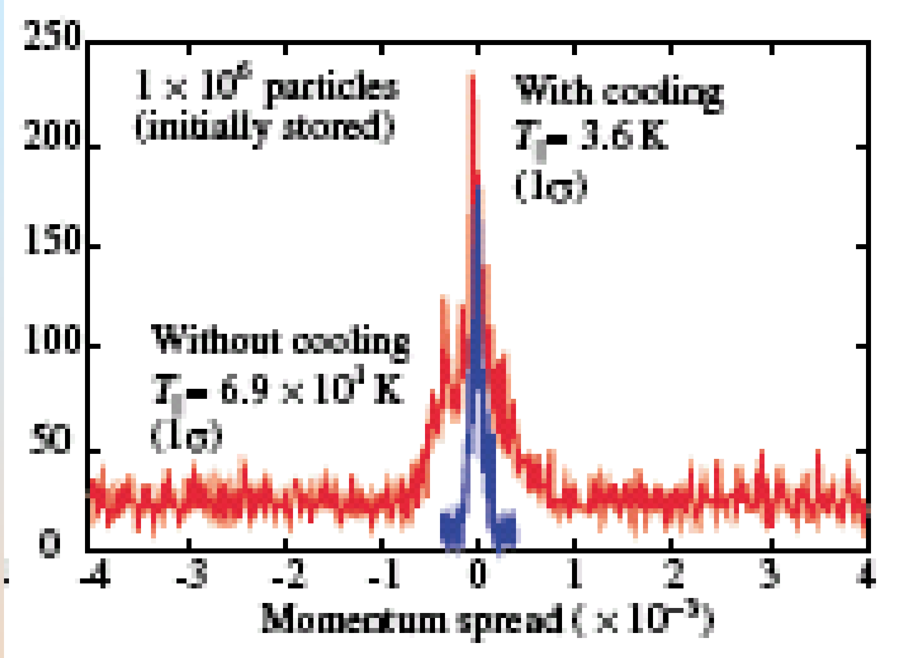


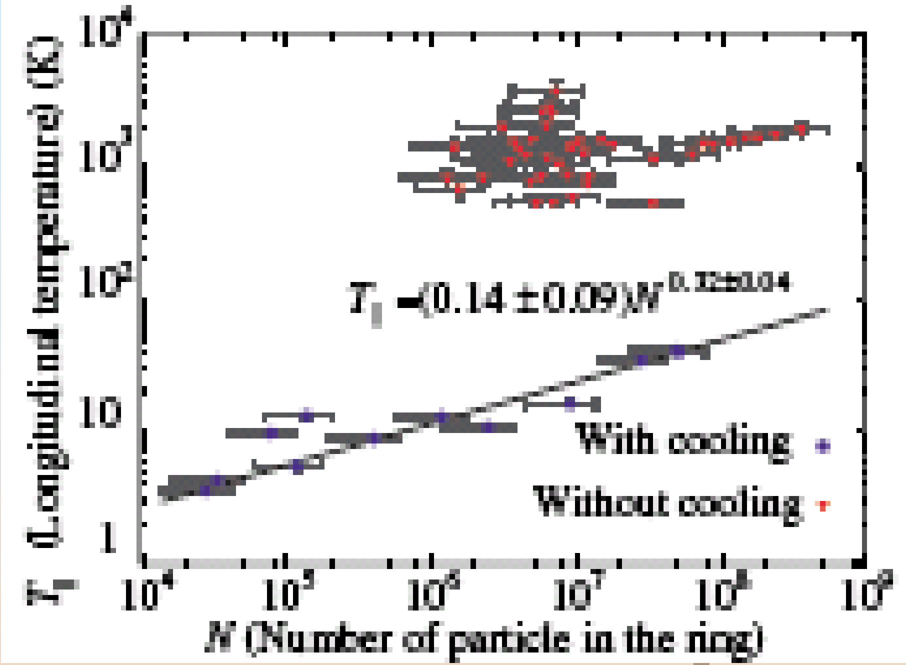
Specification of PAT

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



Laser Cooling of Coasting Beam at S-LSR





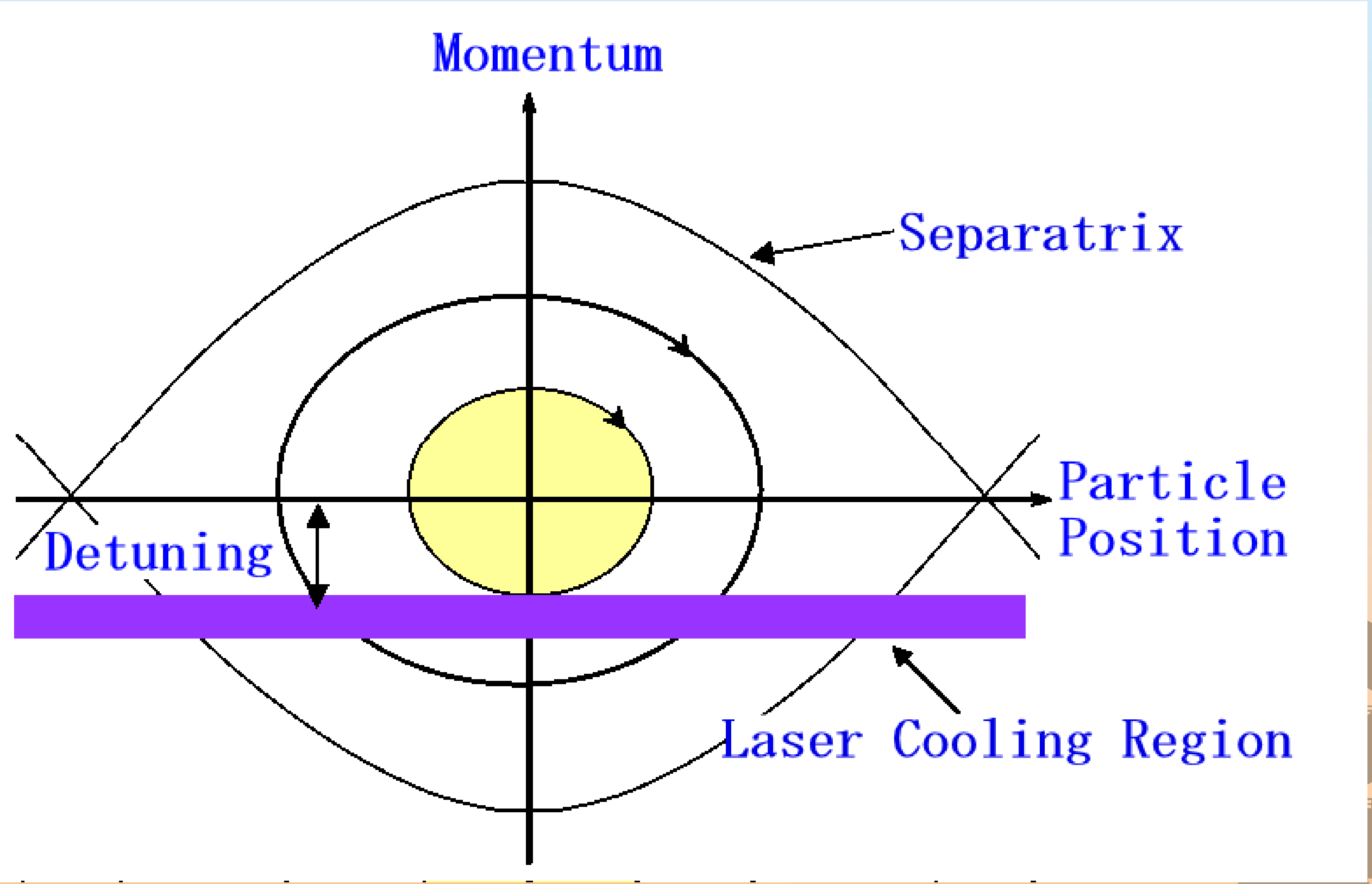
$$k_B T_{\mathrm{L}} = m v_0^2 \left(\frac{\Delta p}{p} \right)^2$$

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

$$T_L = 0.02 T_{\perp}$$

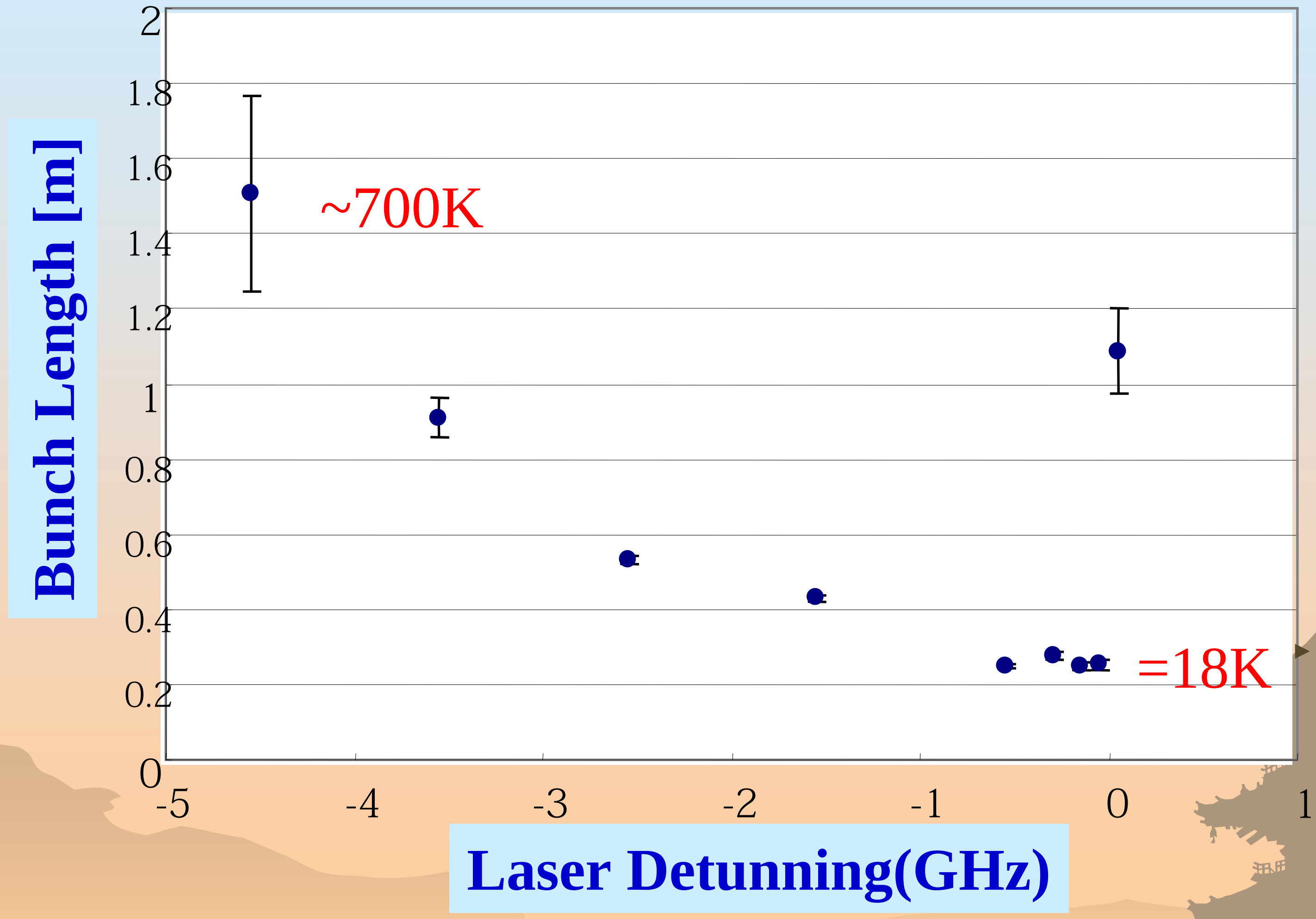
$$\Lambda_{IBS} \propto N \Big/ T_H T_V \sqrt{T_L} \longrightarrow T_L \propto N^{0.4}$$

Bunched Beam Cooling

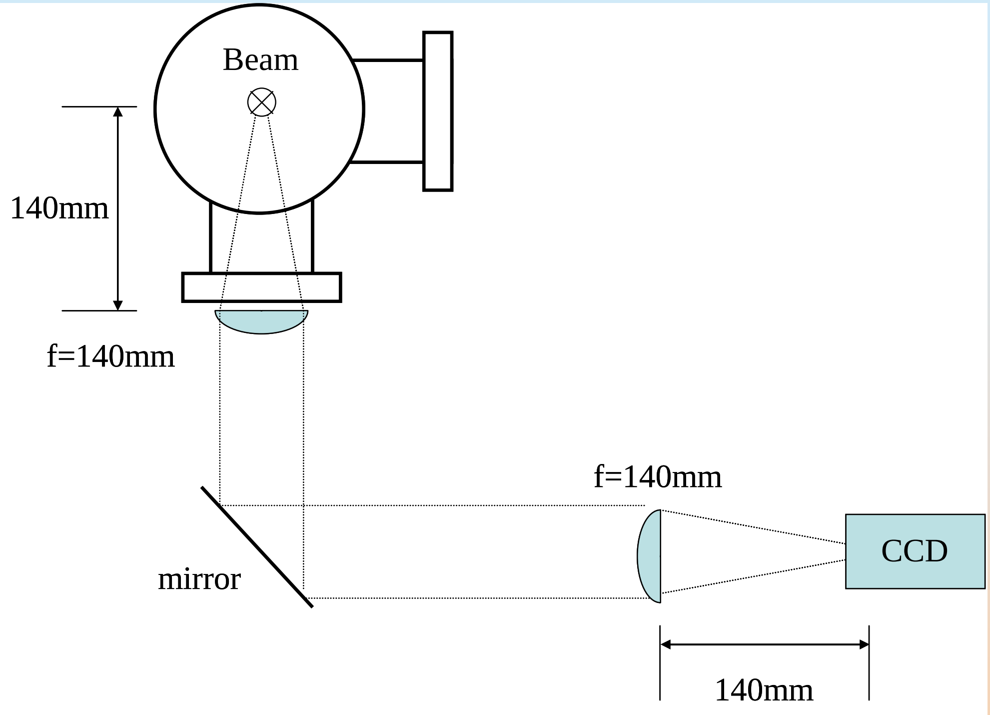


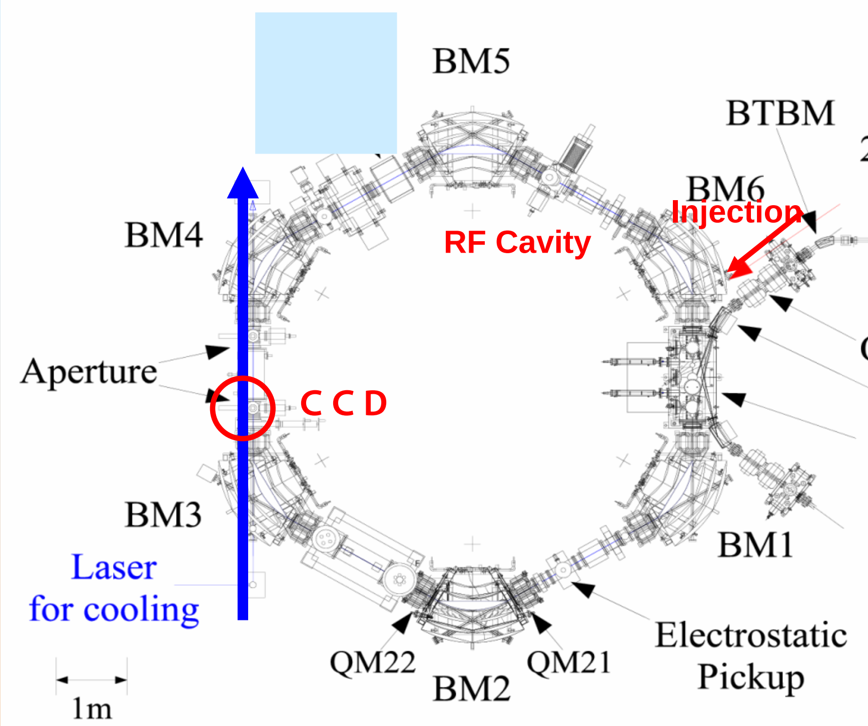
Result of Bunched Beam Cooling

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



Observation of Transverse Beam Size by CCD Camera

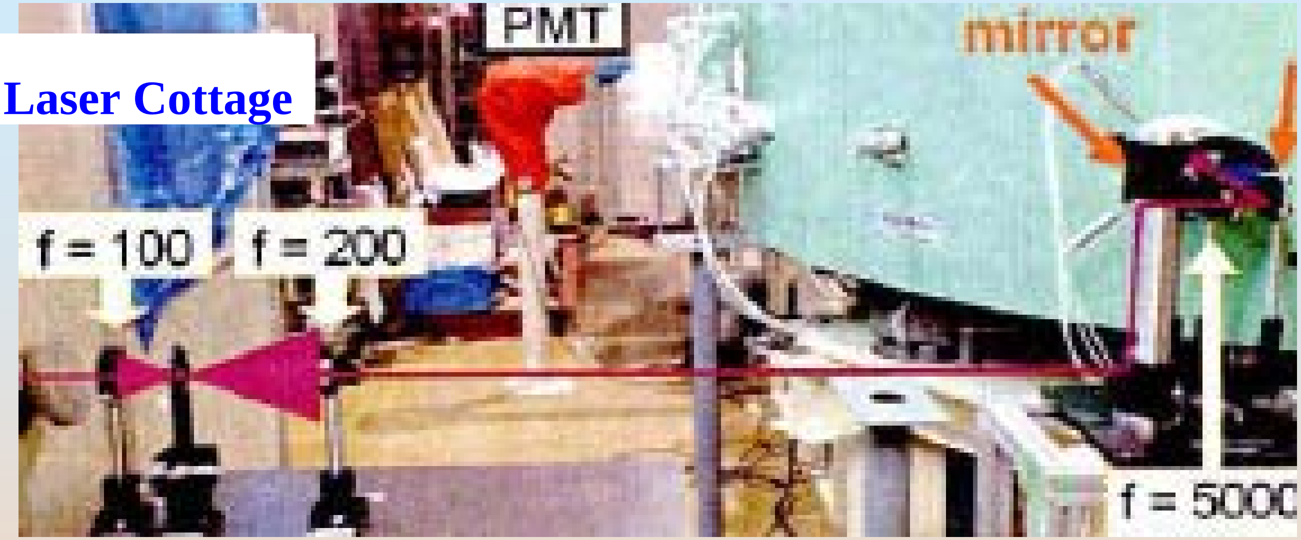


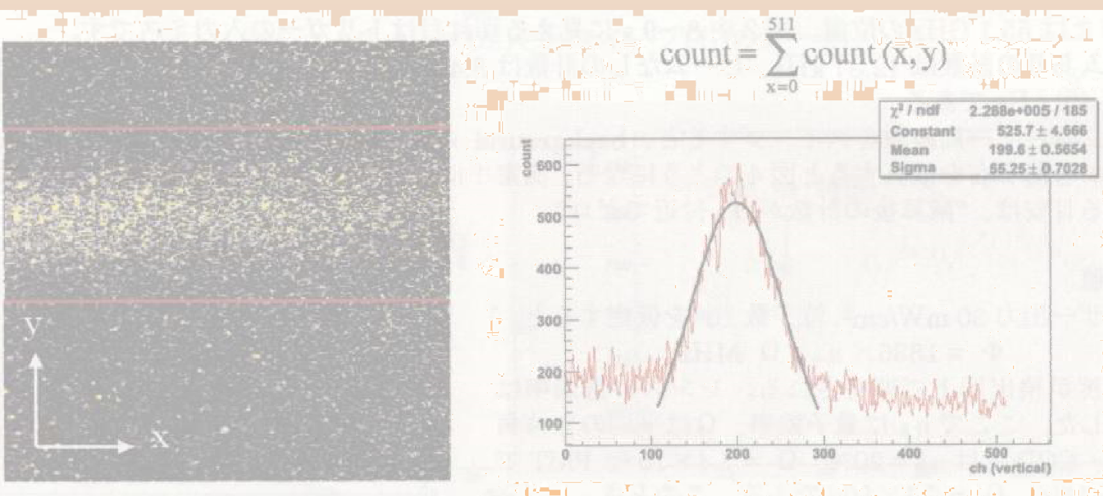


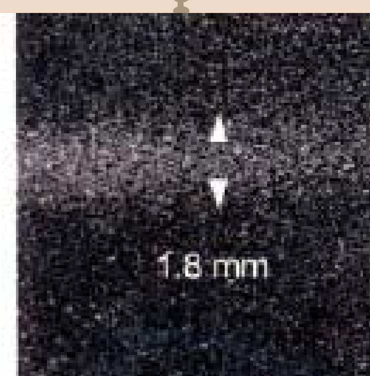
Cooled CCD Camera
(Hamamatsu Photonics C7190-11W)

Ion Observation with Emitted Light

Laser Cottage







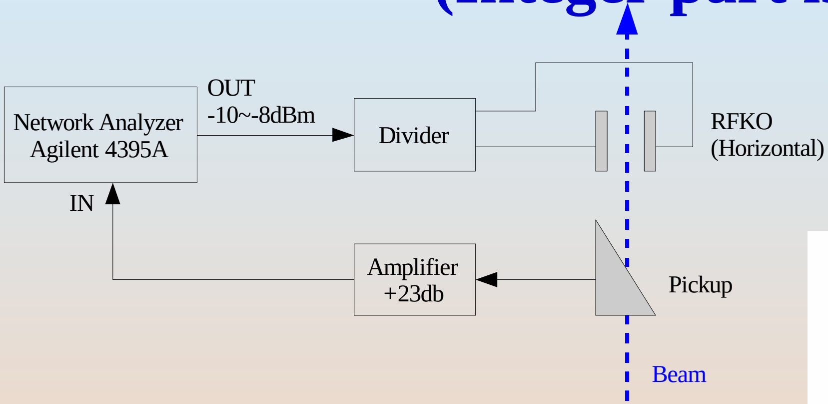
Laser Profile

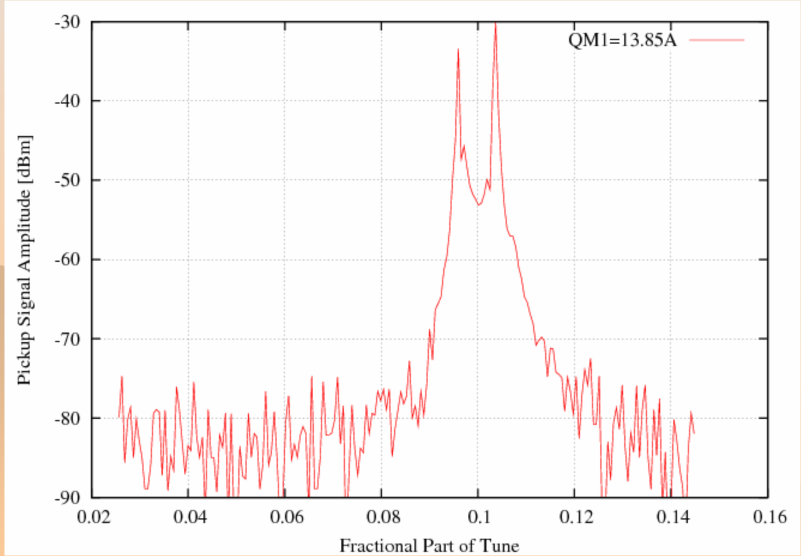
Fluorescent light from the ion beam

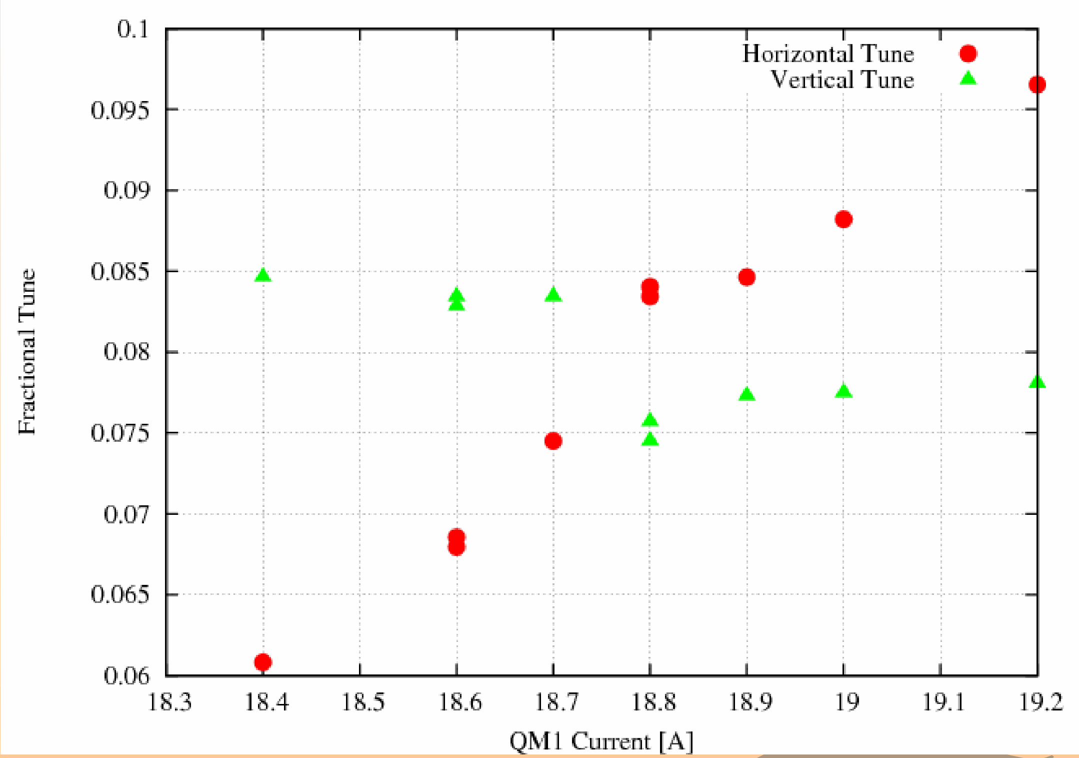
Measurement of Fractional Part of Betatron Tune through Transfer Function Measurement

Beam Transfer Function→Fractional Part of Betatron Tune

(Integer part is obtained from MAD Calculation)

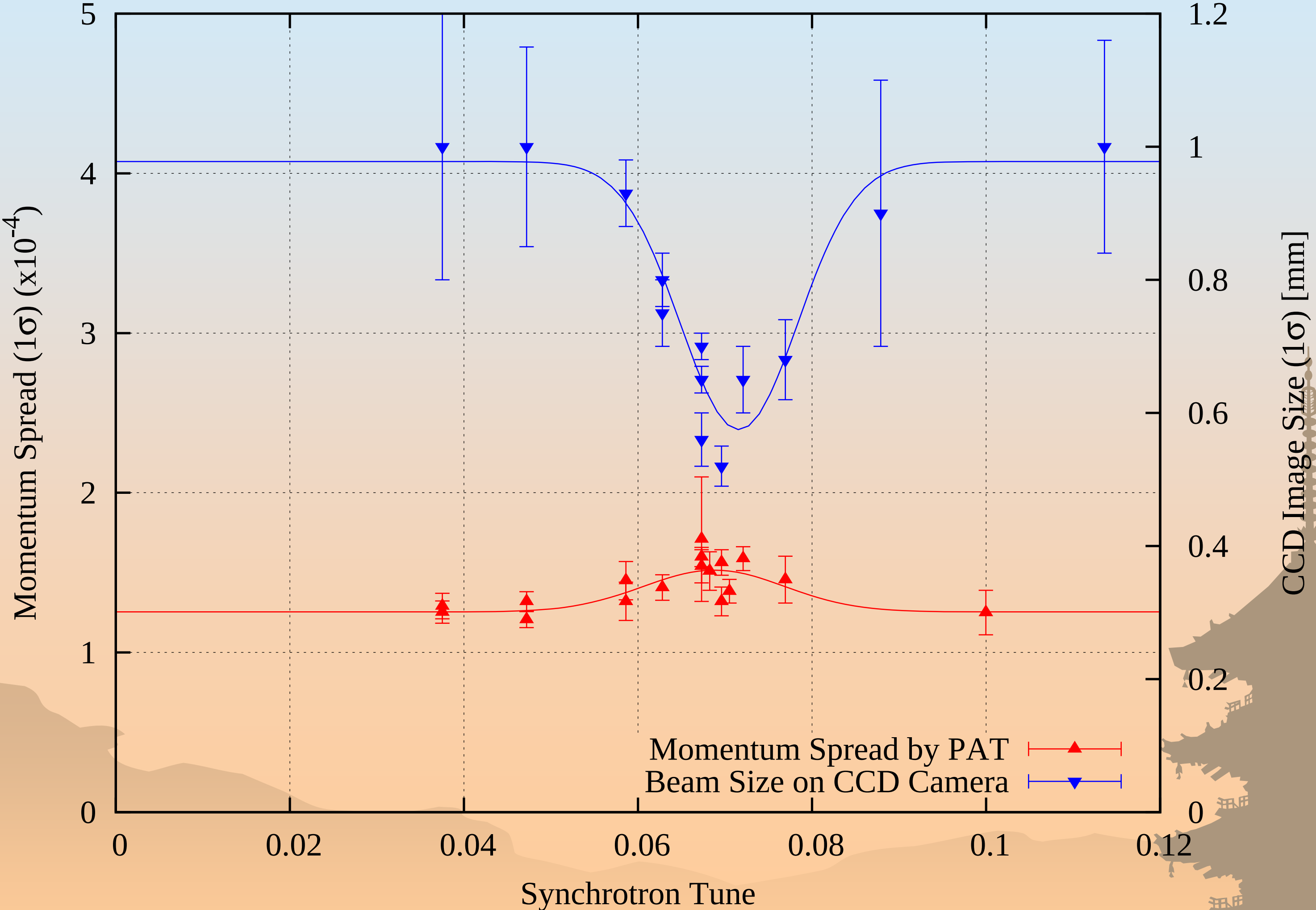






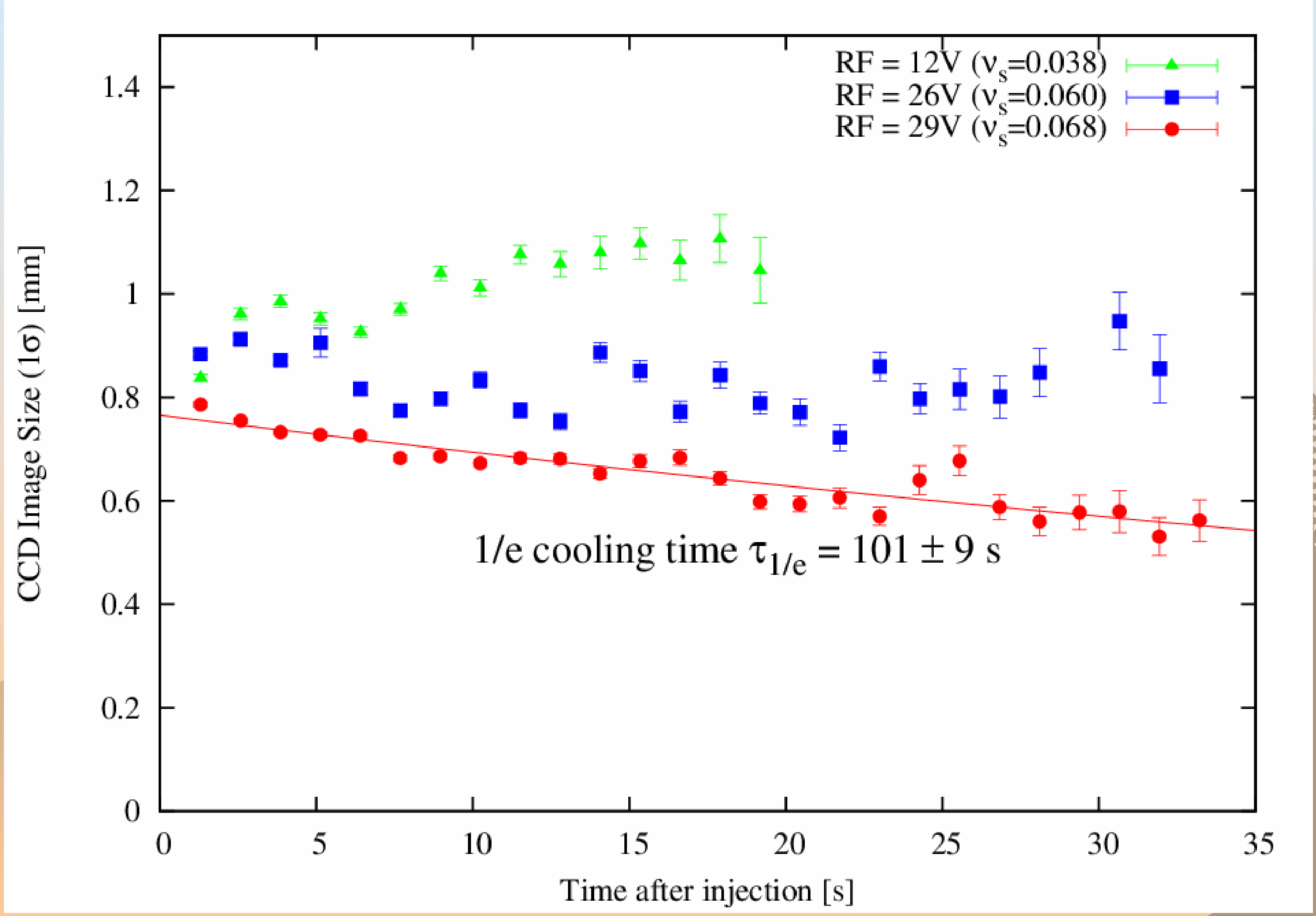
Transverse Laser Cooling by Synchro-Betatron Coupling

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



Time Variation of Transverse Beam Size for Various Synchrotron Tune

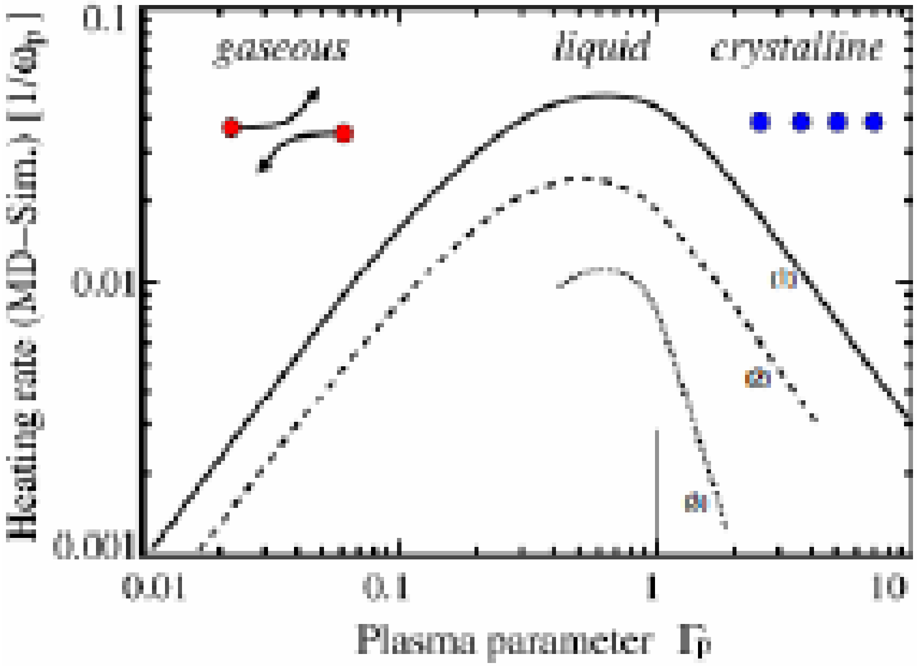
(Beam Intensity 1 x 10^7) **(ν_H, ν_V) = (2.068,1.105)**

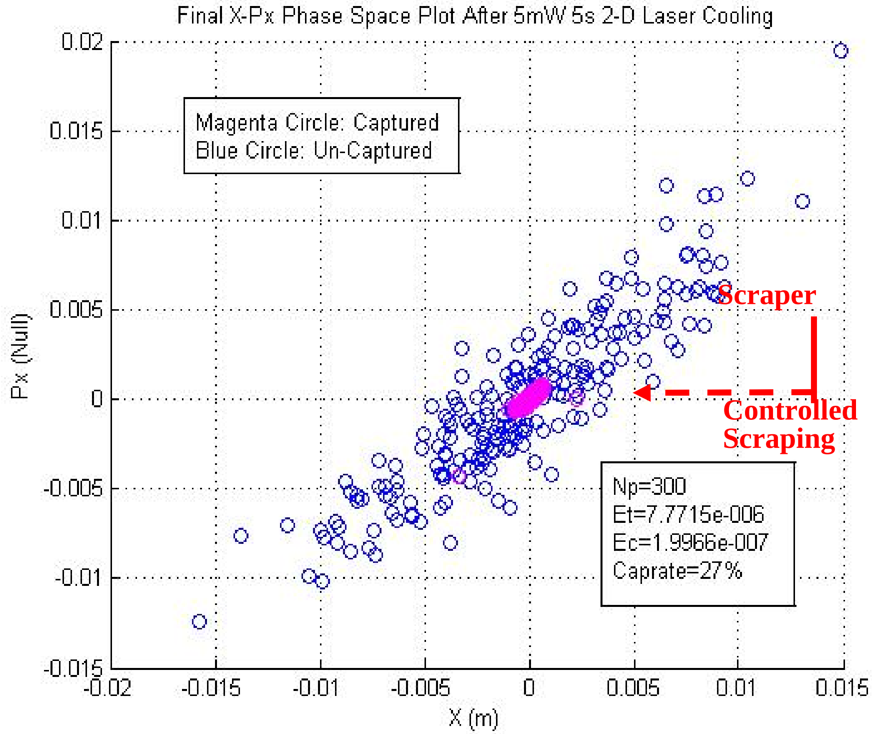


Controlled Scraping to Suppress IBS Effects

By M. Bussmann U. Schramm
and D. Habs et al., SPARC07

He Zhengqi et al., to be published

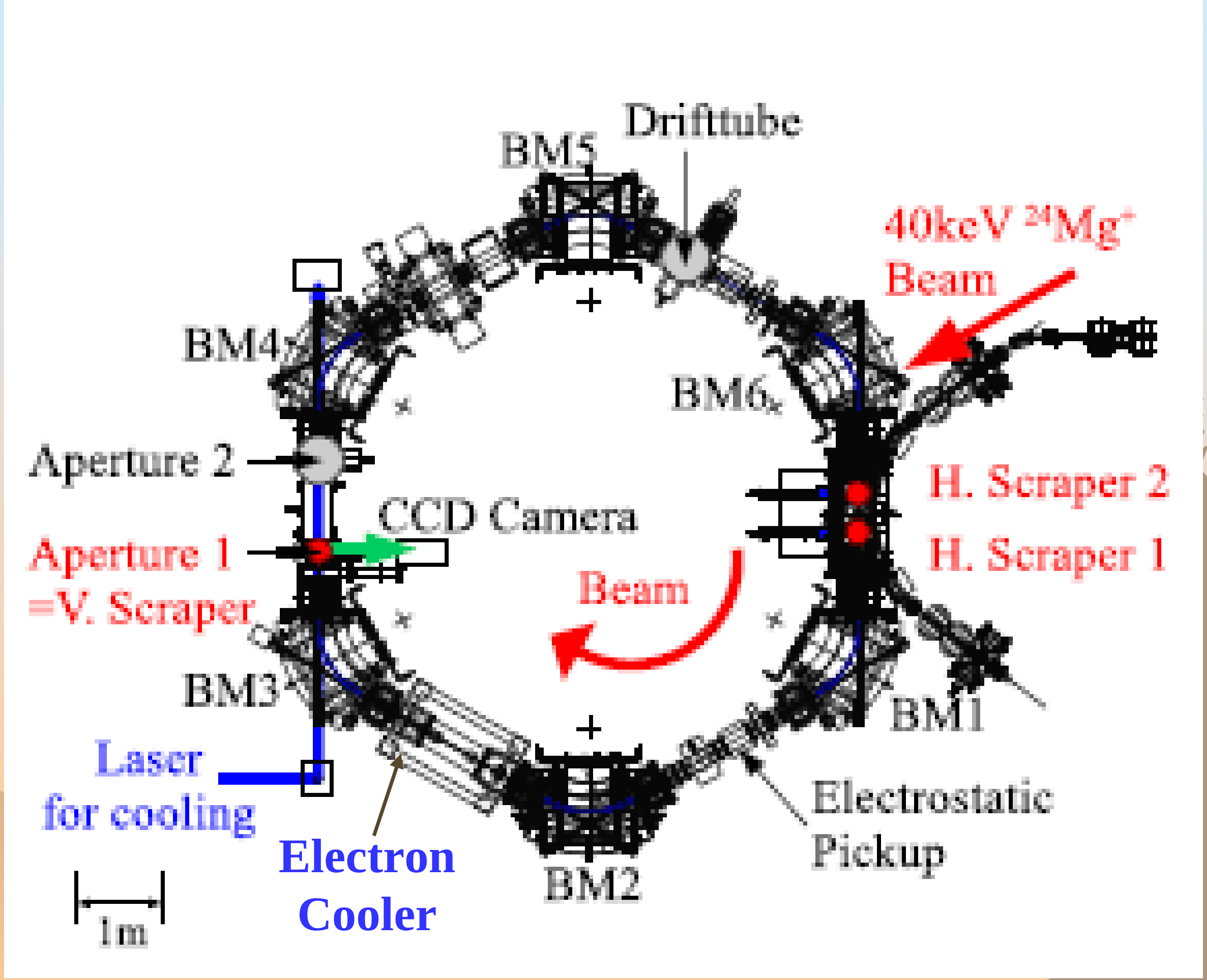




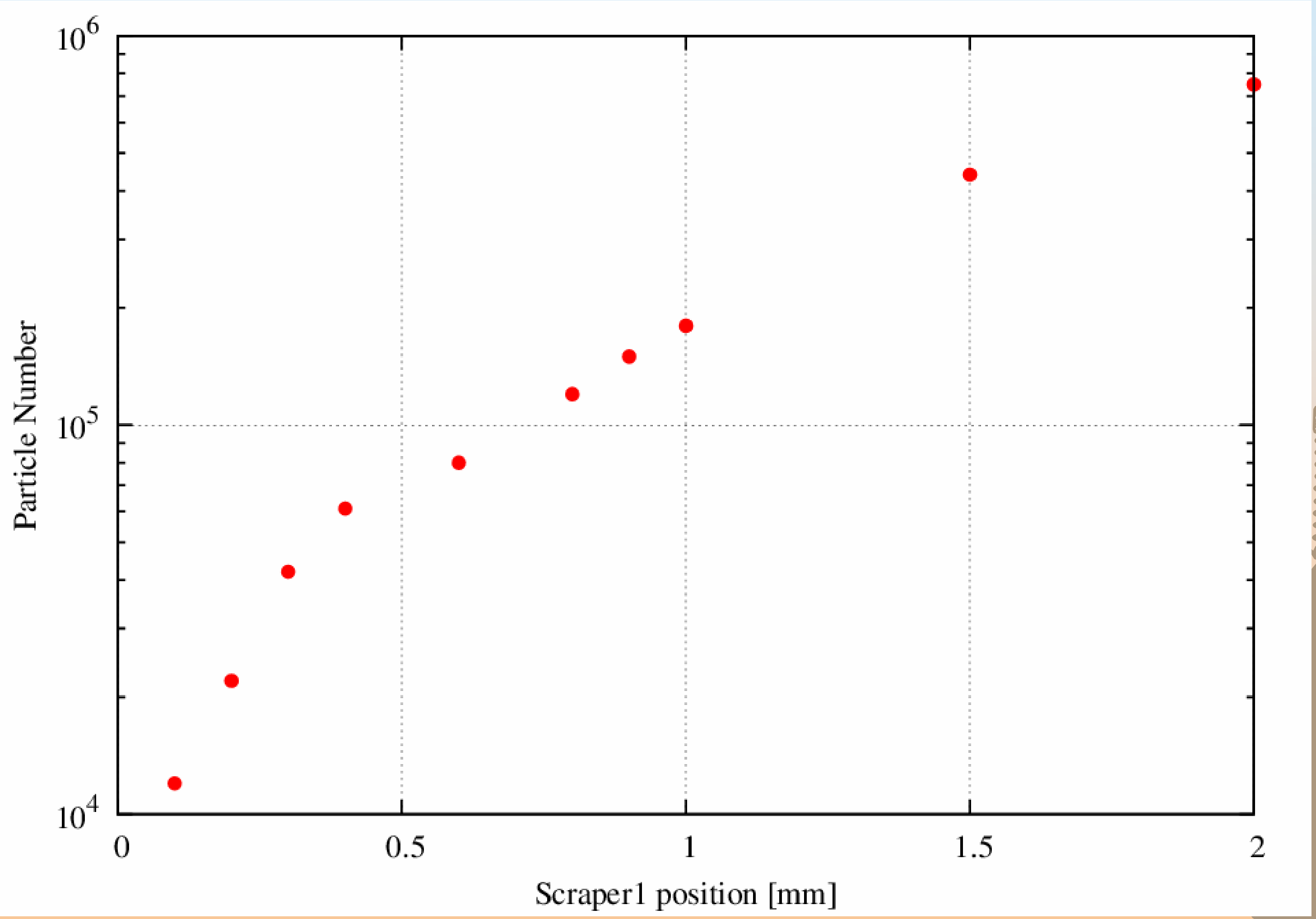
$$\Gamma_p = \frac{E_{Coulomb}}{E_{thermal}} = \frac{Z_{ion}^2 e^2}{4\pi\varepsilon_0 a_{WS} \cdot k_B T_{ion}}, \quad a_{WS} = \left(\frac{4}{3}\pi n_{ion}\right)^{-\frac{1}{3}}$$

(1): Q. Spreiter et al., NIM A 364 (1995), 239
(2): linear ion density reduced by a factor of 10
(3): string, J. Wei et al., PRL 80 (1998), 2606

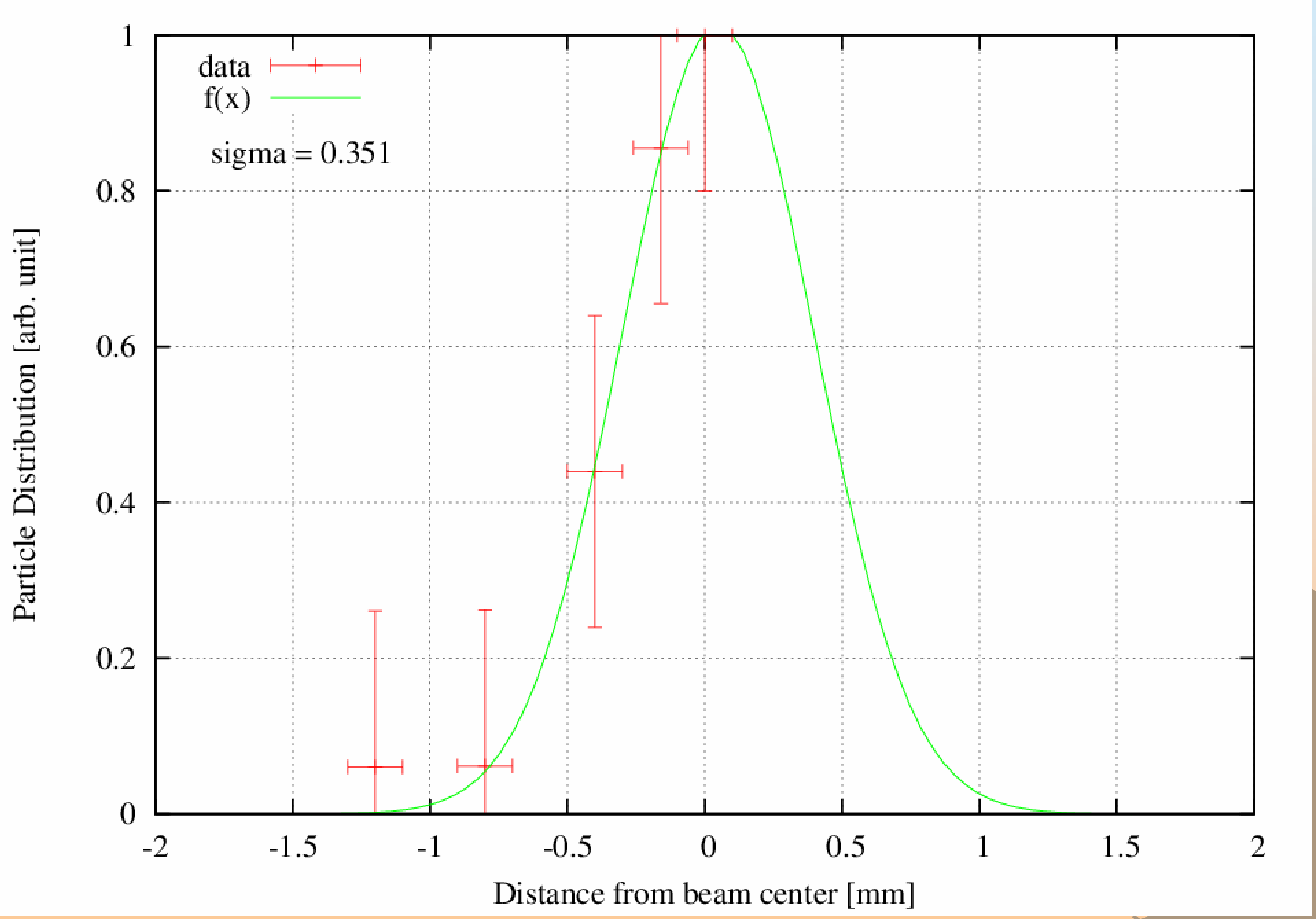
Scraping System for Intensity Reduction and Beam Size Measurement



Relation between Scraper 1 Position and Beam Intensity

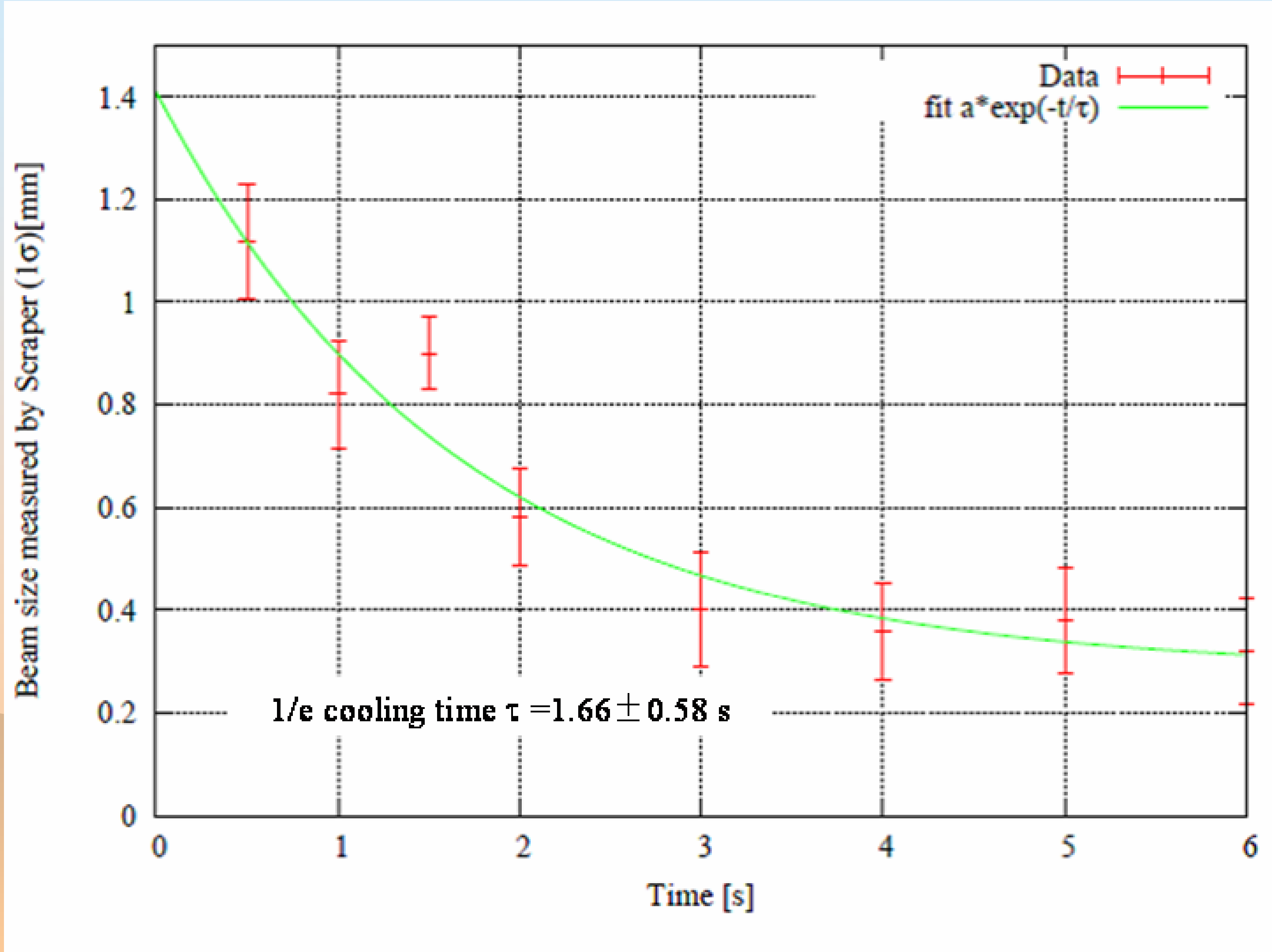


Example of Horizontal Beam Profile Measured by a Horizontal Scraper 2

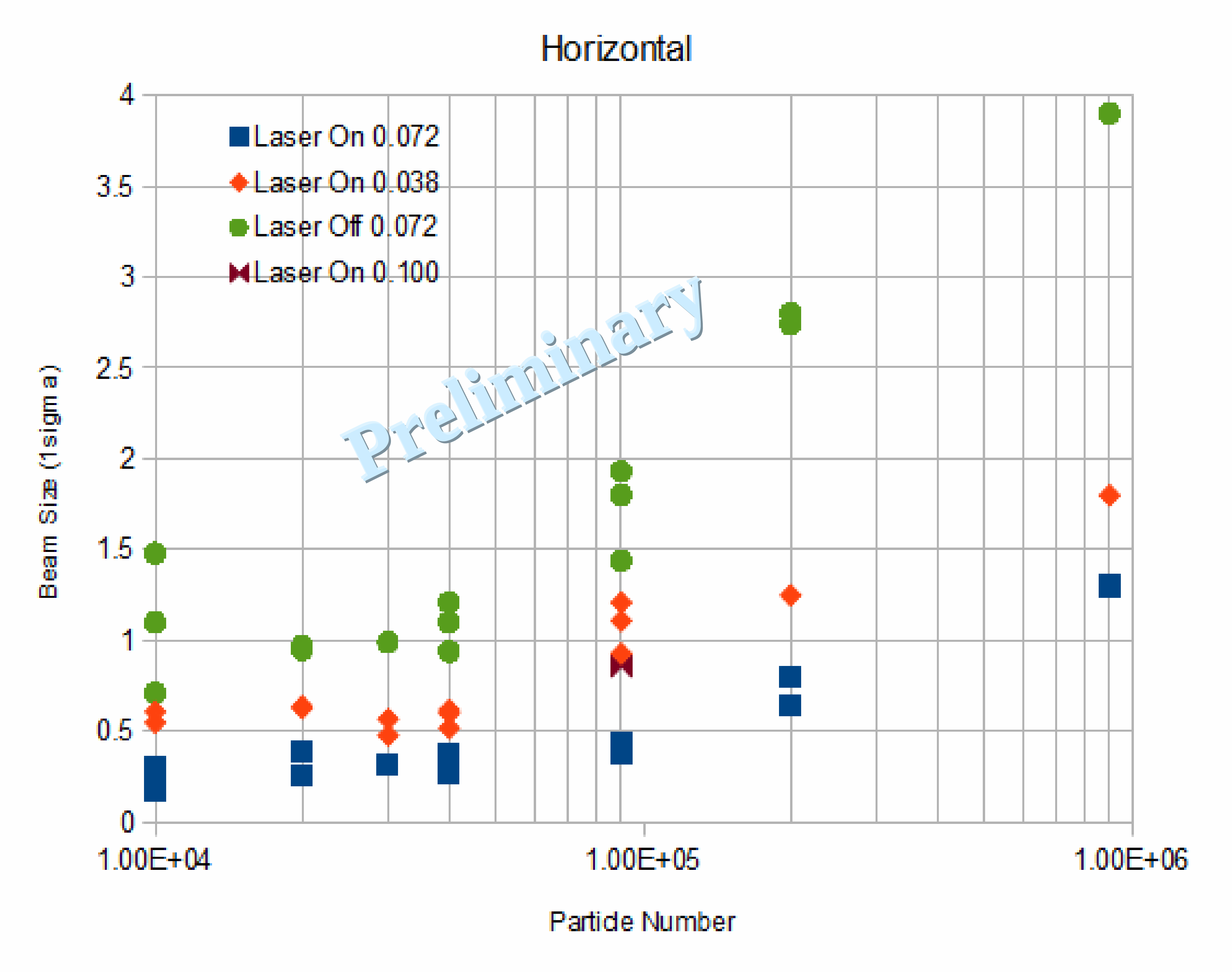


Time Variation of the Horizontal Beam Size

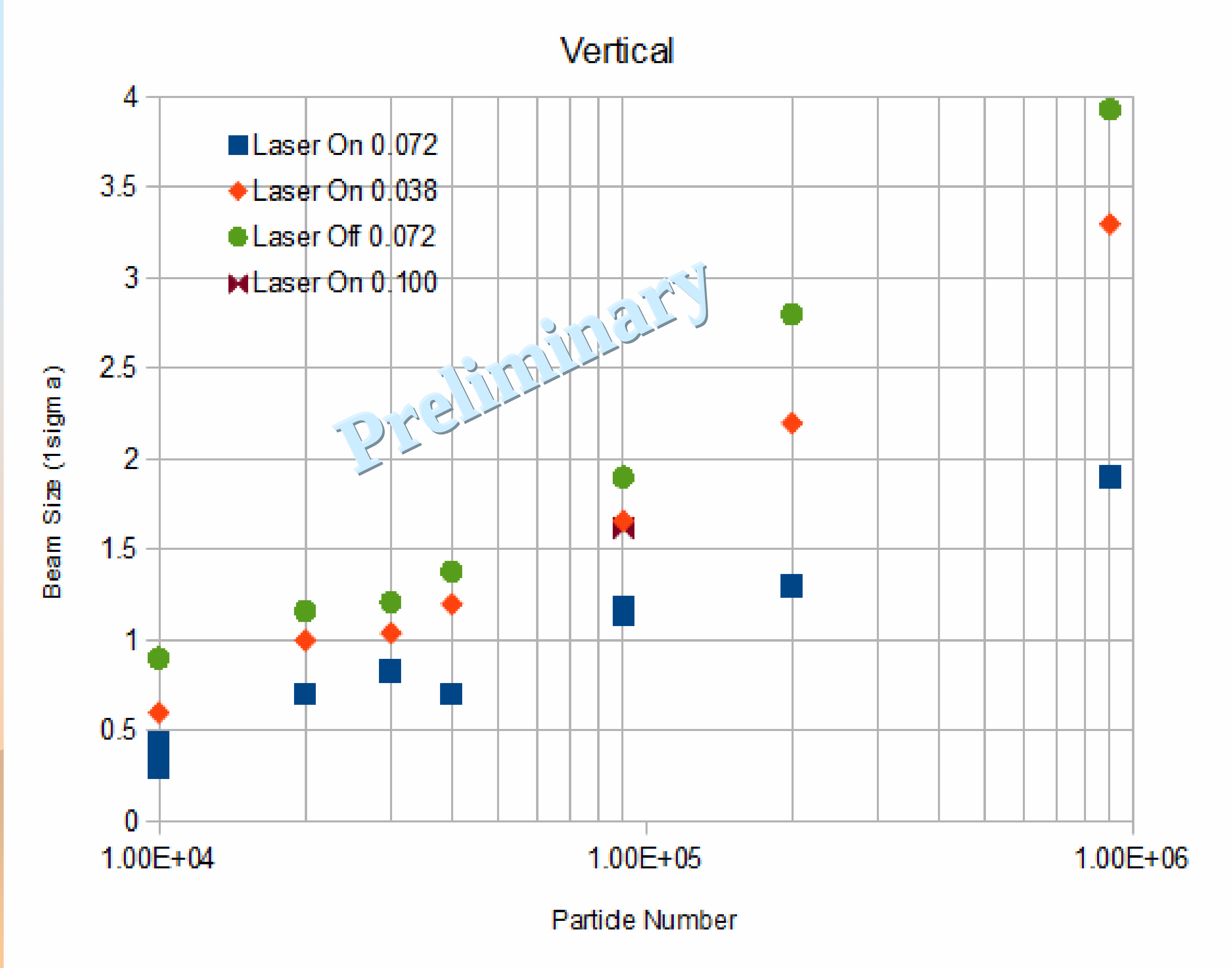
(Beam Intensity 9 x 10^4)



Beam Intensity Dependence of Horizontal Beam Size



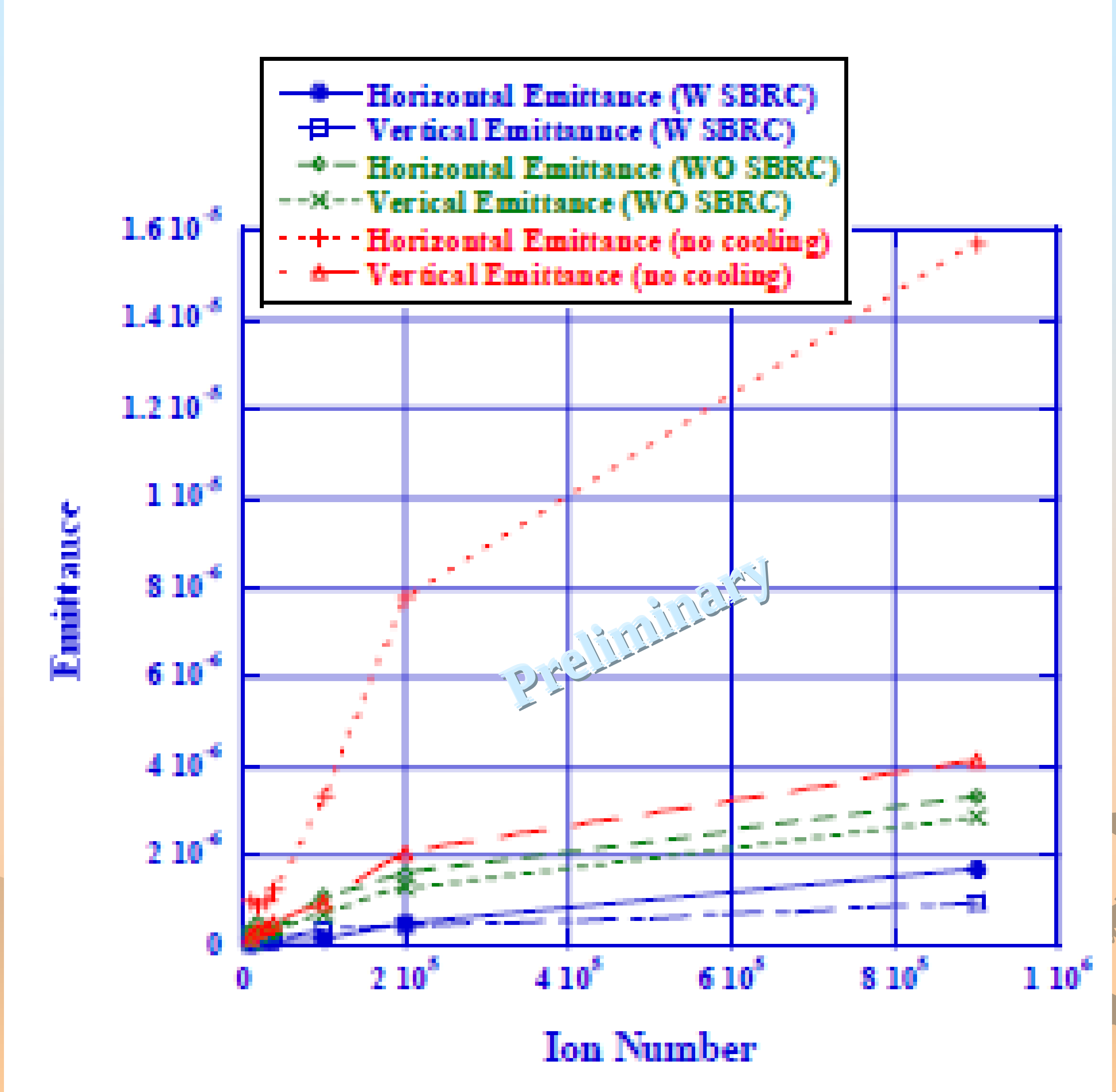
Beam Intensity Dependence of Vertical Beam Size



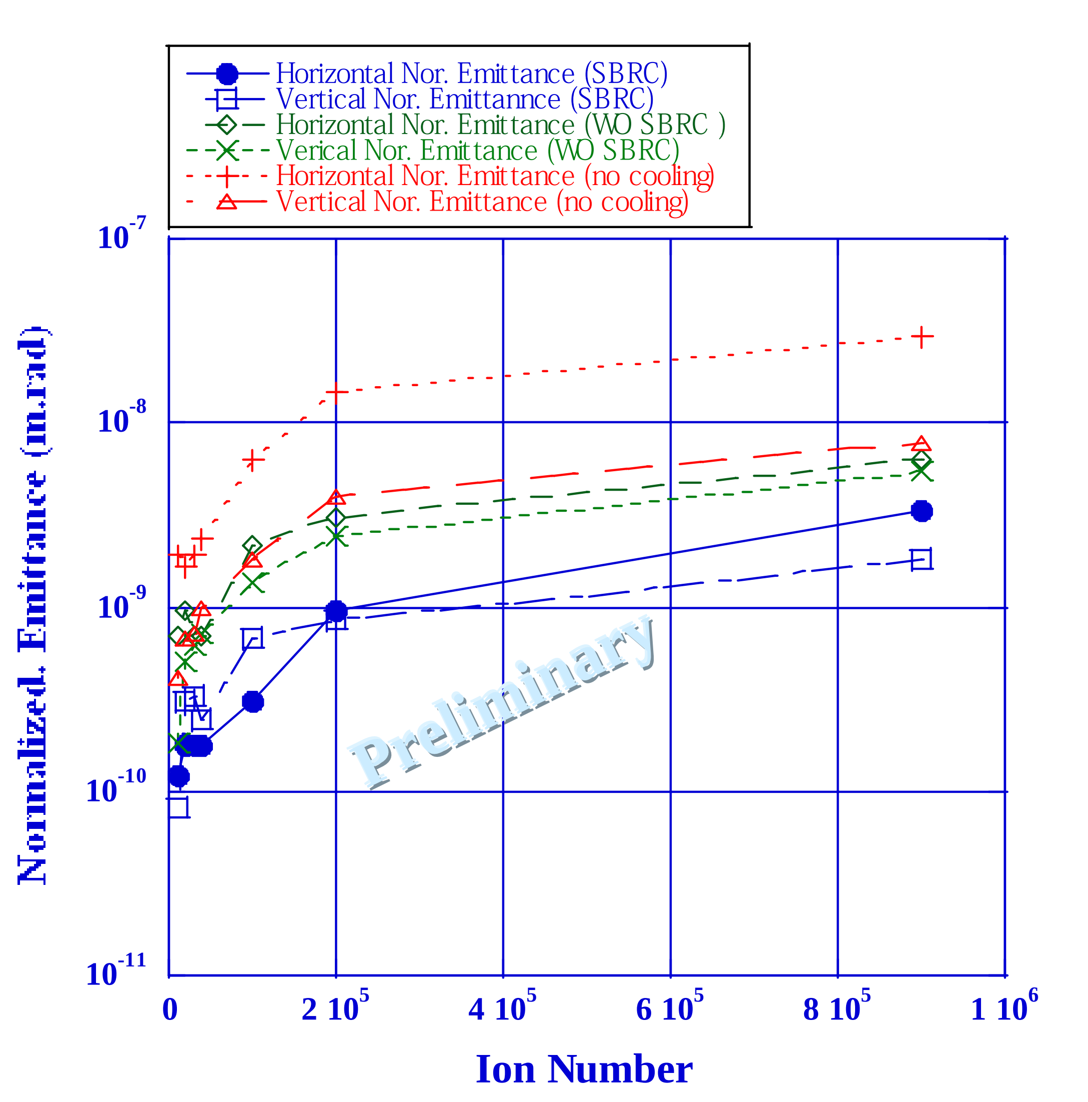
Comparison with Former Data

Year	Method	Ion	Kinetic Energy	Intensity	T	T_H	T_V	Ref
1996	IBS	$^9Be^+$	7.3 MeV	2.0 x 10^7	15	4000	500	[15]
1998	Dispersive cooling	$^9Be^+$	7.3 MeV	1.0 x 10^7	few tens	~500#	~150#	[17]
2001	RFQ	$^{24}Mg^+$	1 eV	1.8 x 10^4	<3 m	$T_\perp$<0.4		[25]
2008	IBS	$^{24}Mg^+$	40 keV	1.0 x 10^7	11	-	500	[18]
2009	W SBRC	$^{24}Mg^+$	40 keV	1.0 x 10^7	27	220$		[20]
2009	WO SBRC	$^{24}Mg^+$	40 keV	1.0 x 10^7	16	-%		[20]
2012	W SBRC	$^{24}Mg^+$	40 keV	1 x 10^4	-	<16~50	7~15	[23]
2012	WO SBRC	$^{24}Mg^+$	40 keV	1 x 10^4	-	<150~190	30	[23]

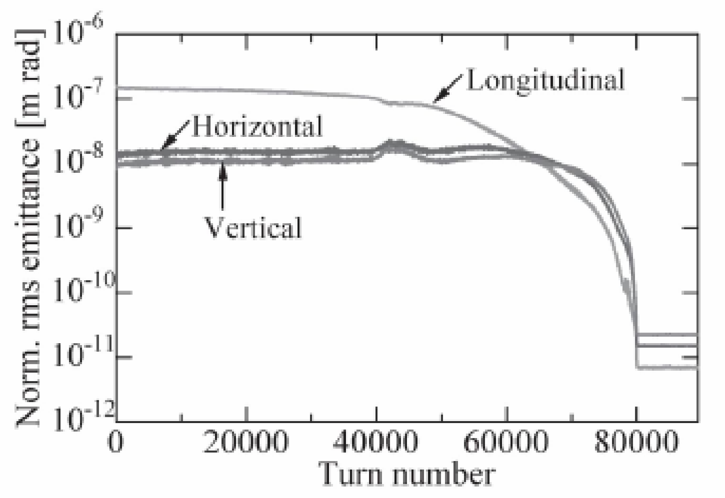
Emittance Variation depending upon Ion Number



Ion Number Dependence of Normalized Emittance



Simulation



Y. Yuri and H. Okamoto, PR-STB, 8 (2005), 114201

Perspective for Future Research

1. Study of 1D Ordering for bunched 7 MeV proton beam (H. Danared's suggestion) and try to extend to 2D by increase of line density (Prof. A. Wolf's suggestion)
2. Increase of cooling efficiency of indirect transverse laser cooling

→further scraping to ~1 x 10^3, where simulation expects transition to string state

→needs improvement of S/N ratio and increase available laser power (pre-cooling?)

Summary

1. ・1D Ordering has been attained for 7 MeV proton at particle number ~2000 and realized the longitudinal temperature of 0.3 K while the transverse temperature is 12 K for particle number of 4000 at the position of β=1.7 m.
2. ・Laser cooling has realized 3.6 K for a coasting beam with the initial beam intensity of 1 x 10^6 and 16 K for a bunched beam with the beam intensity of 1 x 10^7. Vertical temperature of the coasting beam became to be 500 K through IBS.

   ・Indirect transverse laser cooling with the use of SBRC reached the averaged temperatures of 16~50 K and 7~15 K, for horizontal and vertical directions, respectively, (correspond to emittance of several times 10^{-8} m・rad), which are lowest ever attained by laser cooling except for the case of PALLAS dealing with 1 eV $^{24}Mg^+$ ion beam

Acknowledgement

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H. Okamoto, K/ Osaki, Hiroshima U., Higashi-Hiroshima, Japan,

Y. Yuri, JAEA, Takasaki, Japan

I. N. Meshkov, A. V. Smirnov, E. Syresin, JINR, Dubna, Moscow Region, Russia,

M Grieser, MPI-K, Heidelberg, Germany

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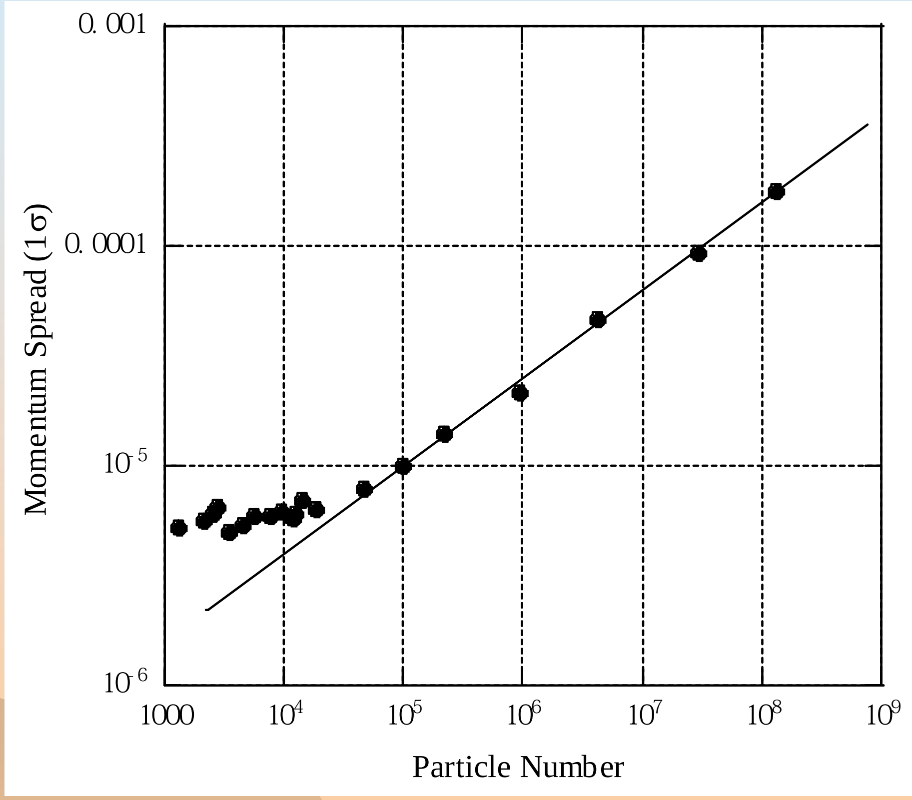
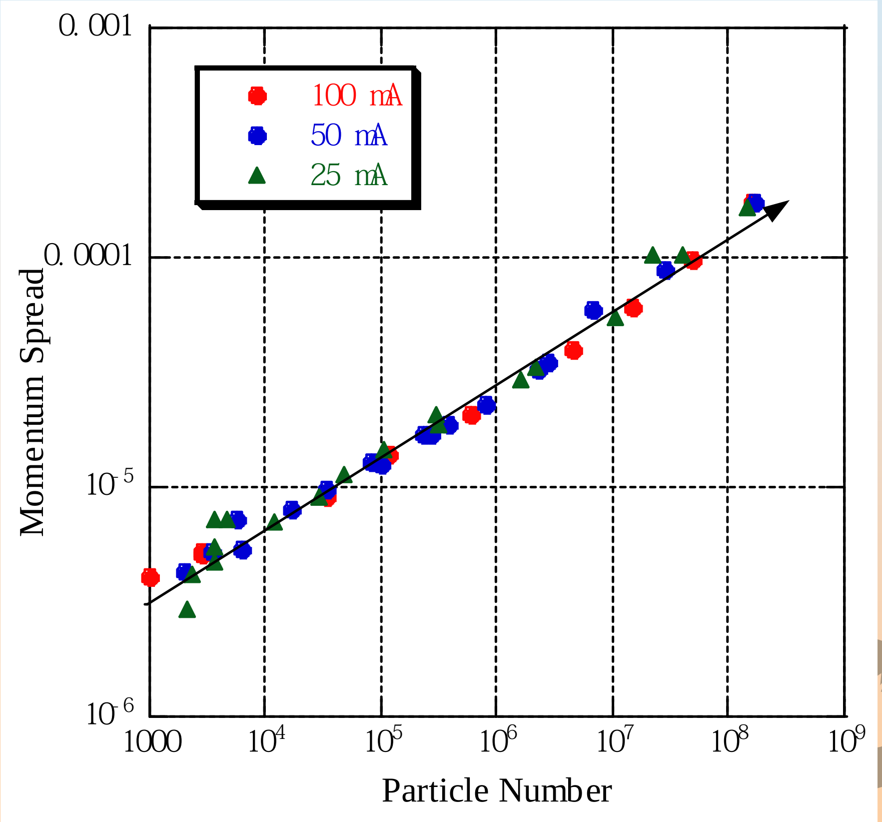
Thank you for your kind attention！

For Further Discussion

Fractional Momentum Spread vs Particle Number

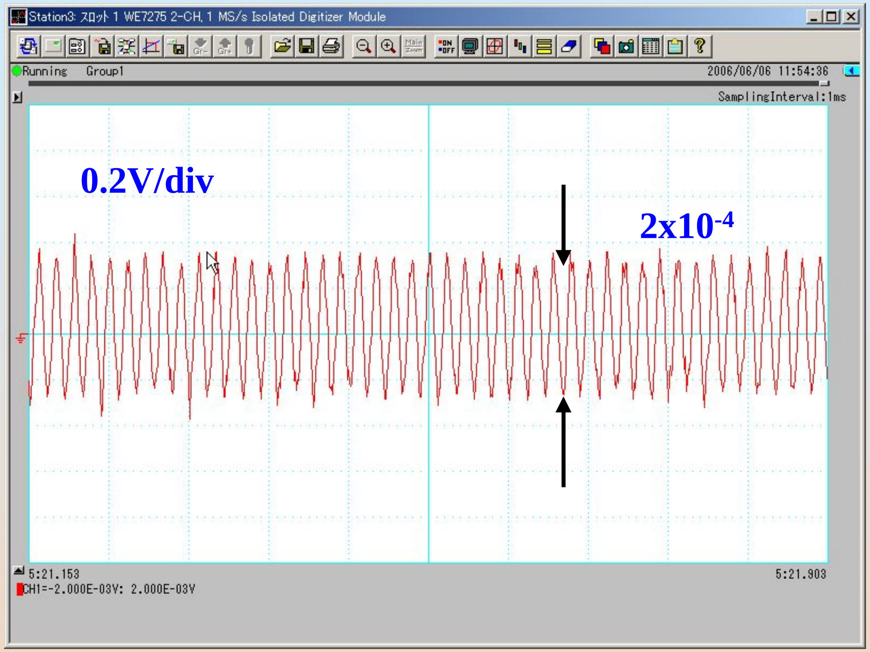


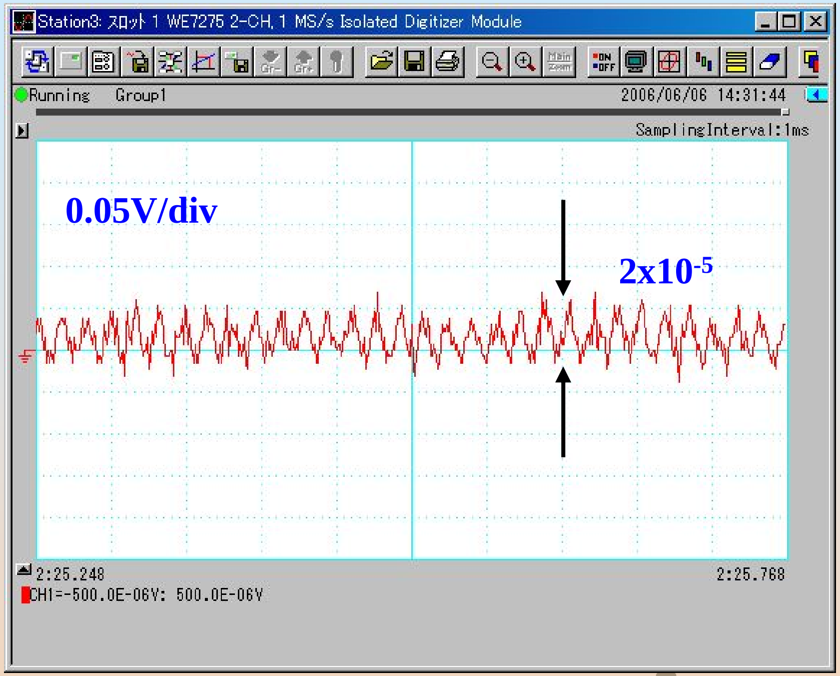


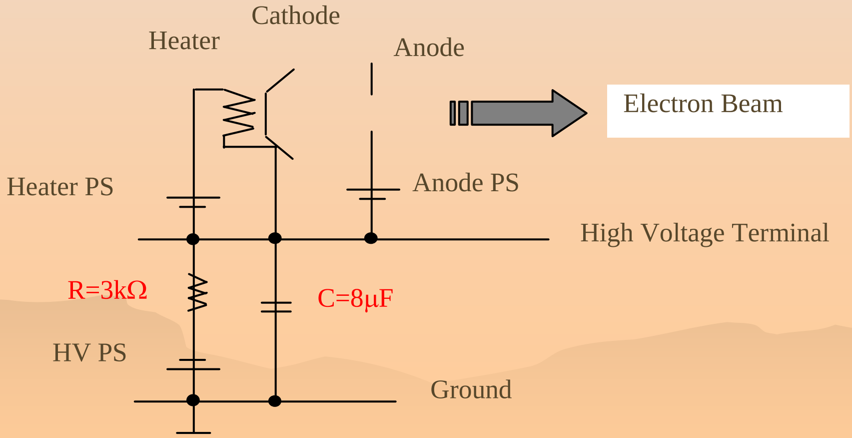
Data in Feb., 2006

Data on the 8th, June, 2006

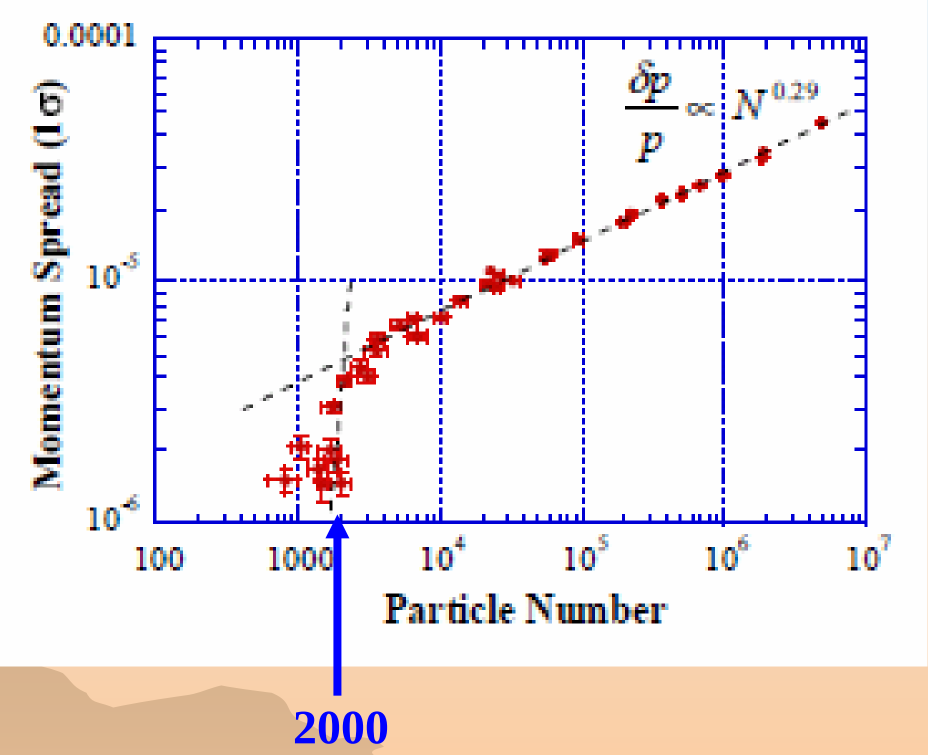
Reduction of Ripple in Electron Gun

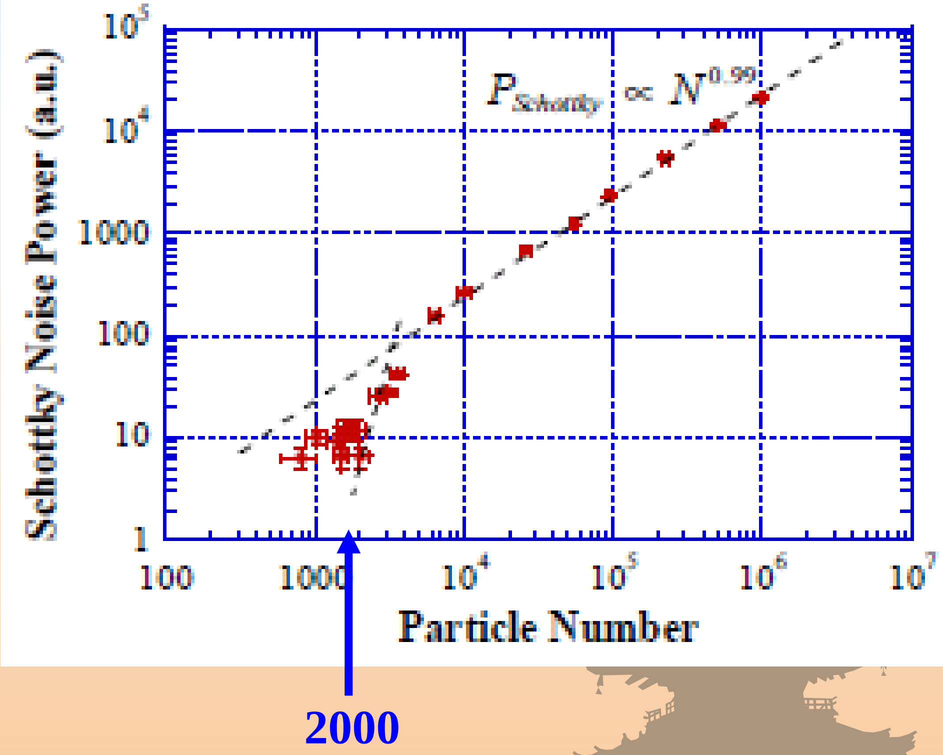






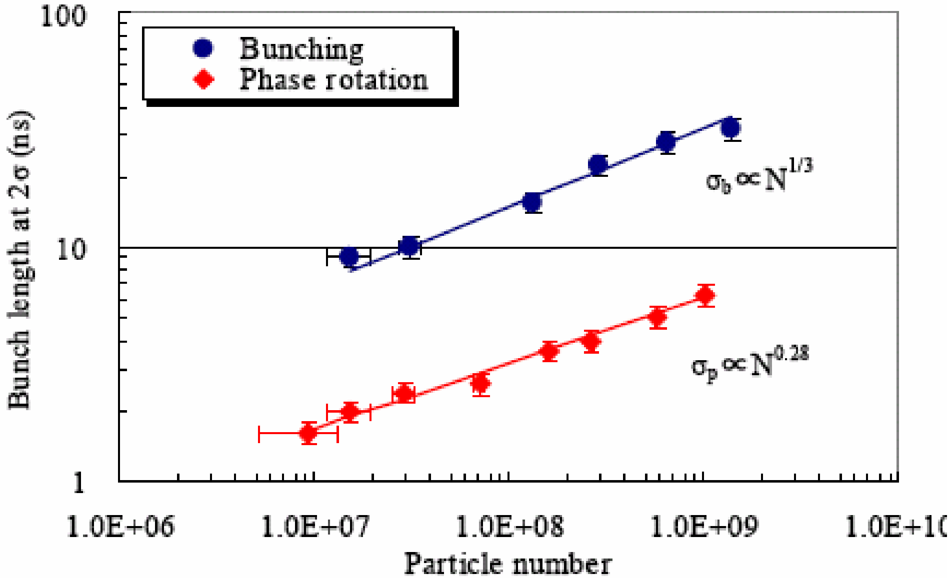
Abrupt Jump of Momentum Spread and Schottky Power

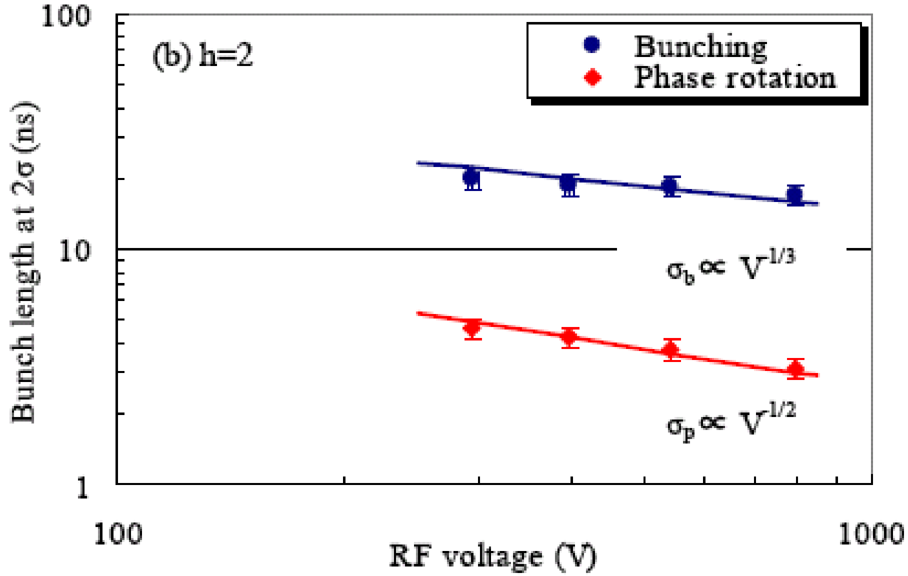




T. Shirai et al., PRL, 98 (2007) 204801

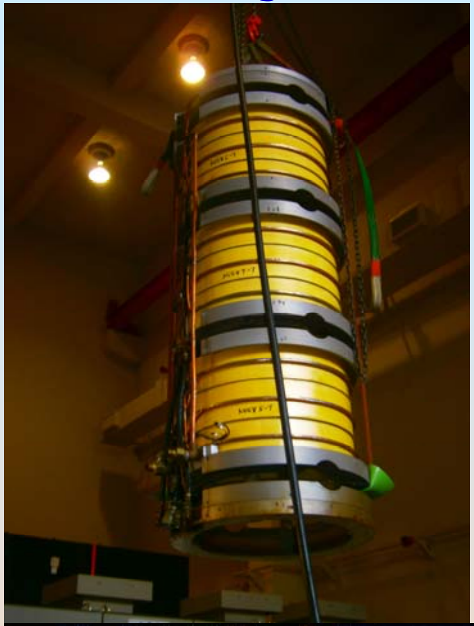
Pulse Length Ever Attained 7 MeV Protons

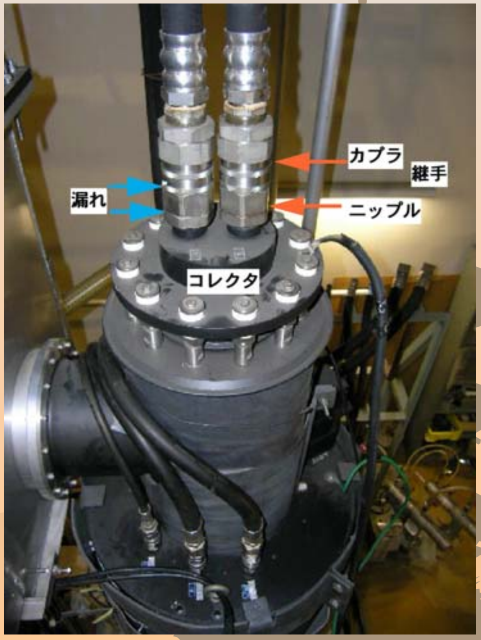




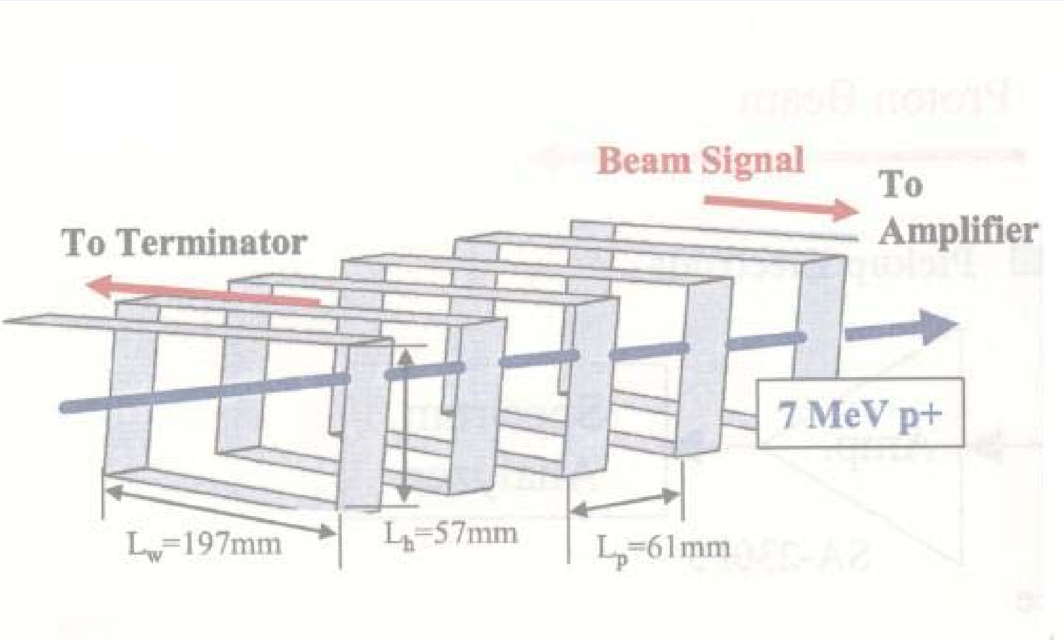
Particle Number Dependence **RF Voltage Dependence**

Repair of Klystron





Structure of Schottky Pick-Up

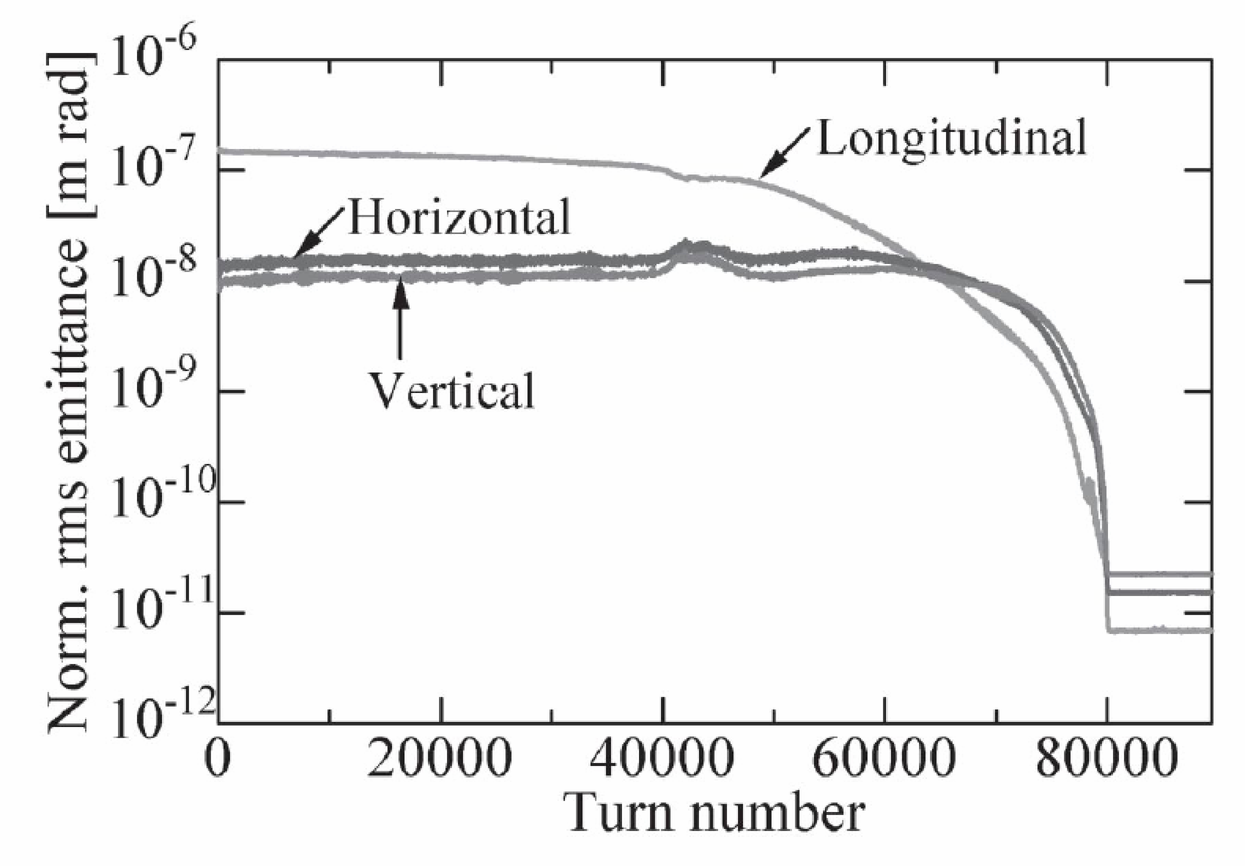


Develped at TARN of INS for Stochastic Momentum Cooling (H. Yonehara et al., INS-NUMA-49)

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)**

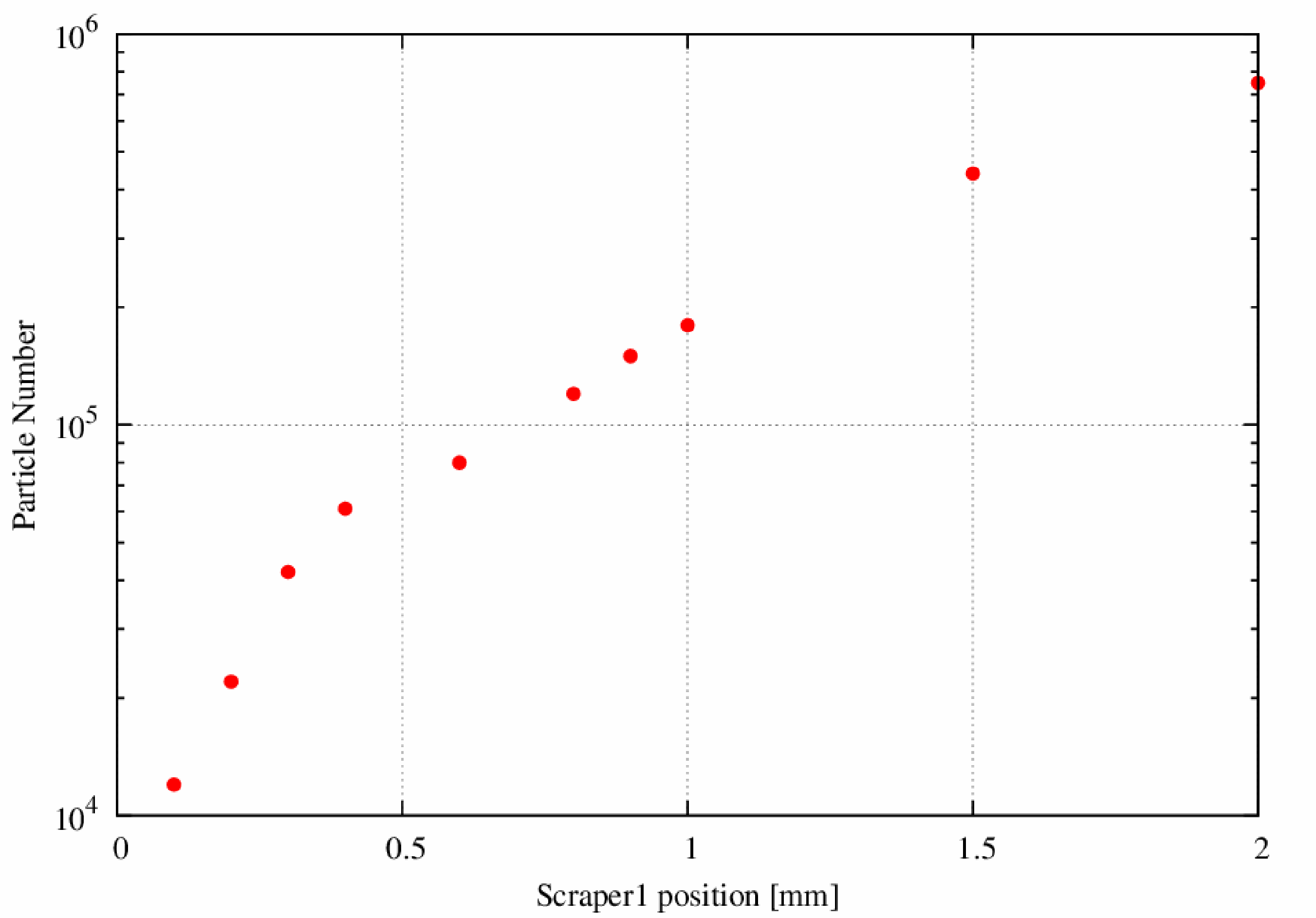
3 D Laser Cooling expected by Simulation



ν_H-ν_s=integer,

ν_H-ν_V=integer

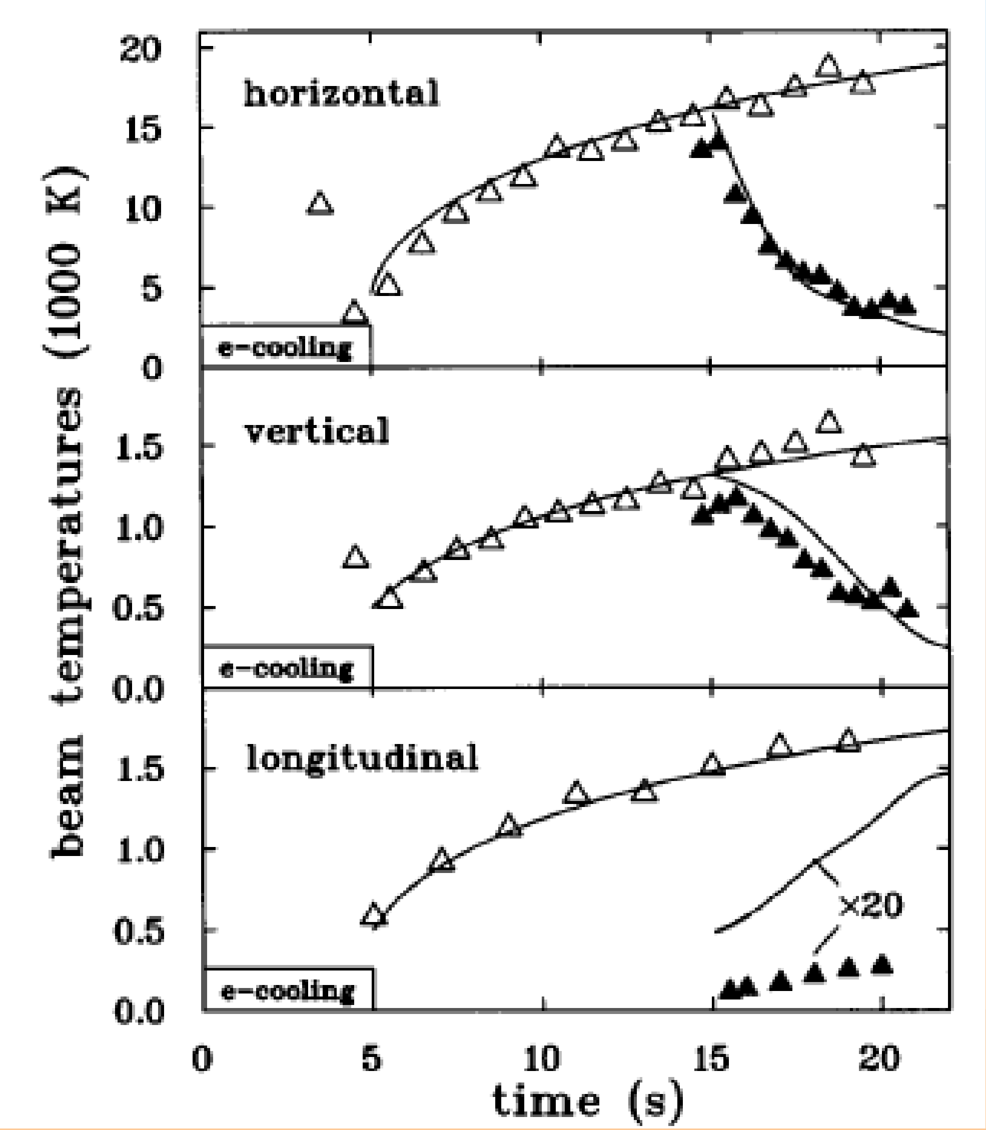
Y. Yuri and H.Okamoto,
Phys. Rev. ST-AB, 8,114201 (2005)



10^6
10^5
10^4
Particle Number
0
0.5
1
1.5
2
Scraper1 position [mm]

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

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



3×10^7 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)

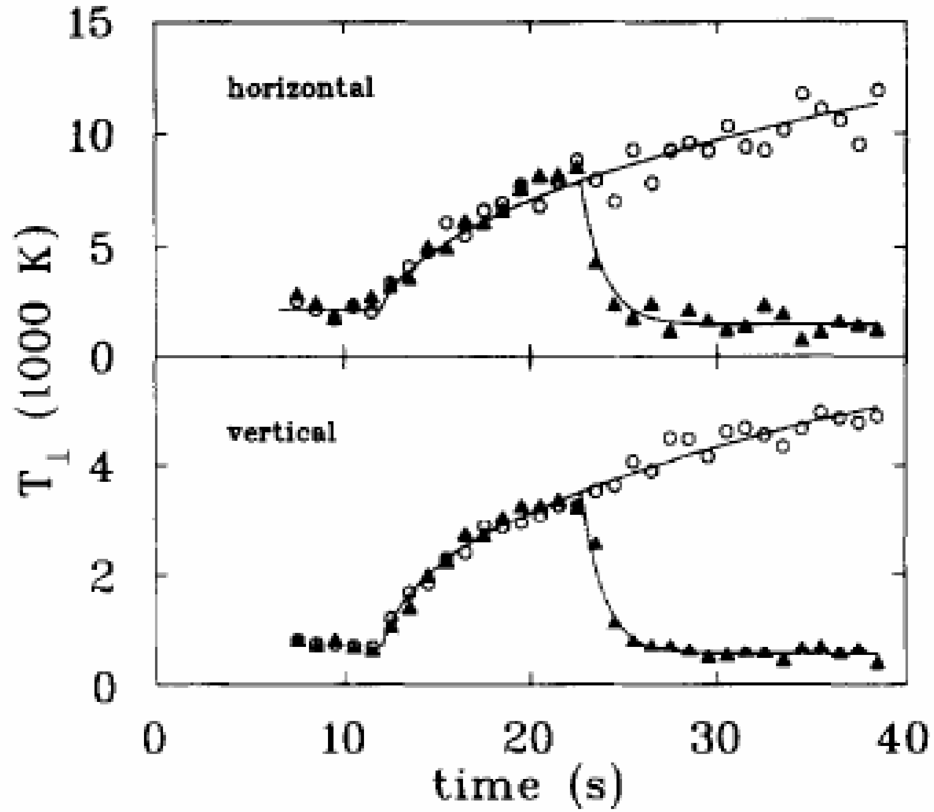
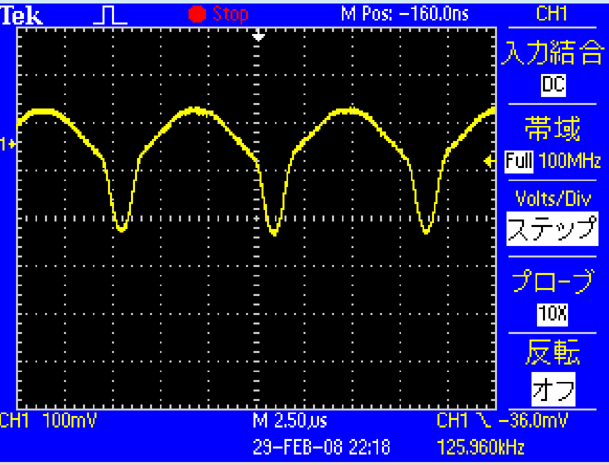


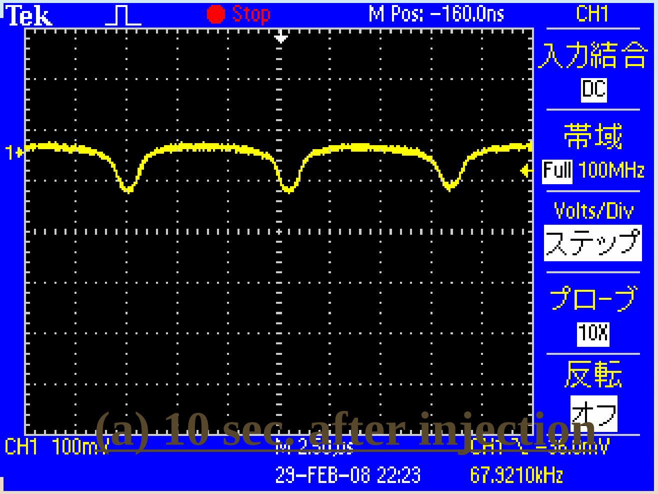
Fig. 1. Temporal evolution of the transverse beam temperatures. The open circles show the beam "blowup" after switching off the electron cooling at t = 12 s. The filled triangles represent corresponding measurements with laser cooling switched on at t = 22 s. The solid lines are shown to guide the eye.

2 x 10^6 ions
σ~1.0 mm

Two components in longitudinally laser cooled beam

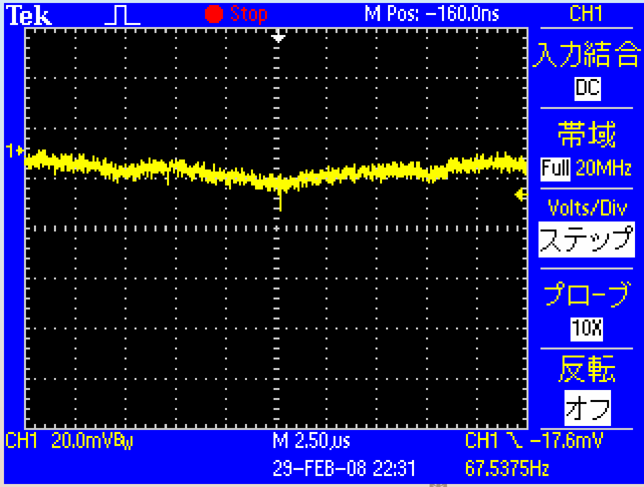


(a) 10 sec. after injection



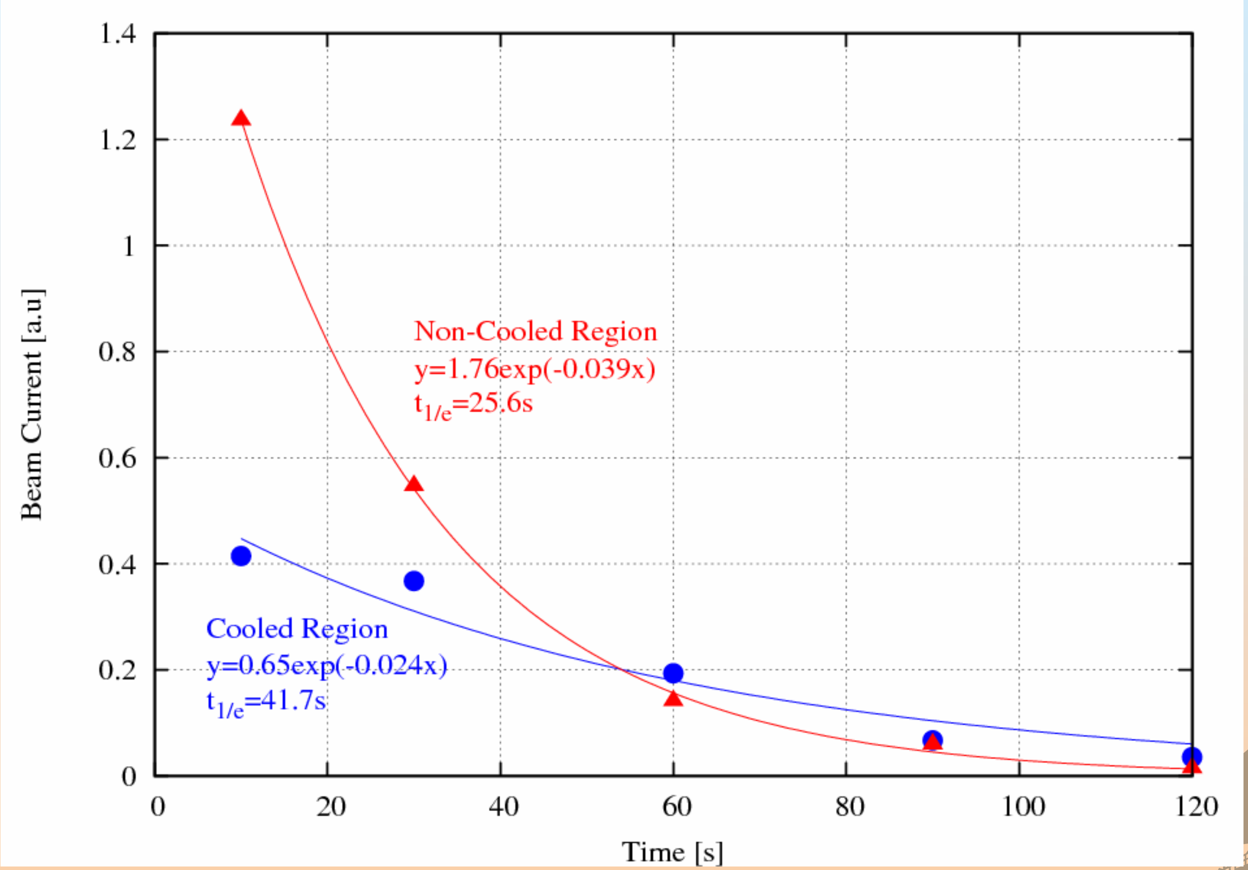
(a) 10 sec. after injection

(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: $T \sim 2$ K. $T_{\perp} \sim 11$ 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 $T \sim 3.6$K
   - Bunched beam on resonance $T \sim 24$ K, $T_{\perp} \sim 200$ K

     off resonance $T \sim 15$ K, $T_{\perp} \sim 600$ 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

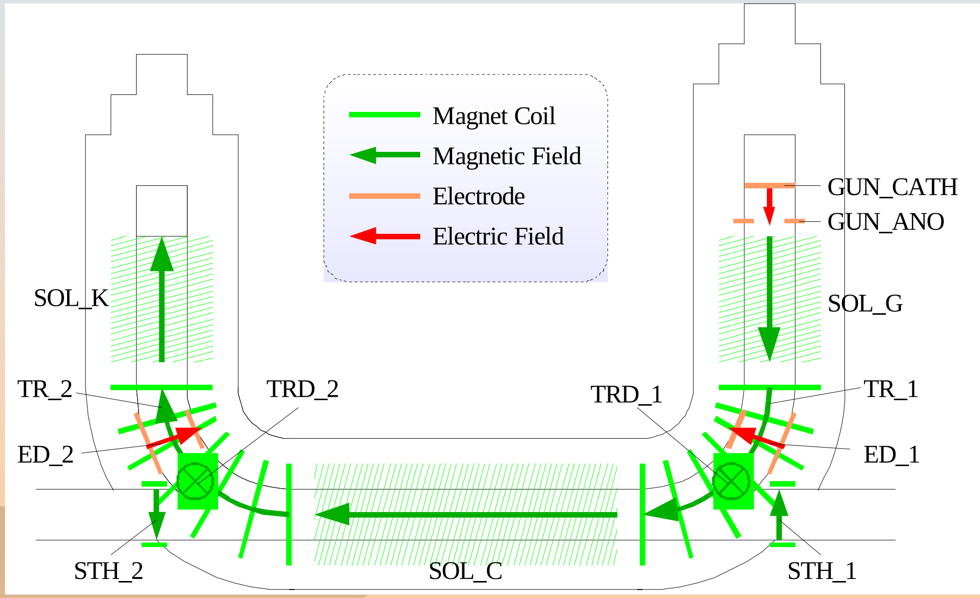
   Optimization of longitudinal bunched beam cooling selecting out the hot ion beams

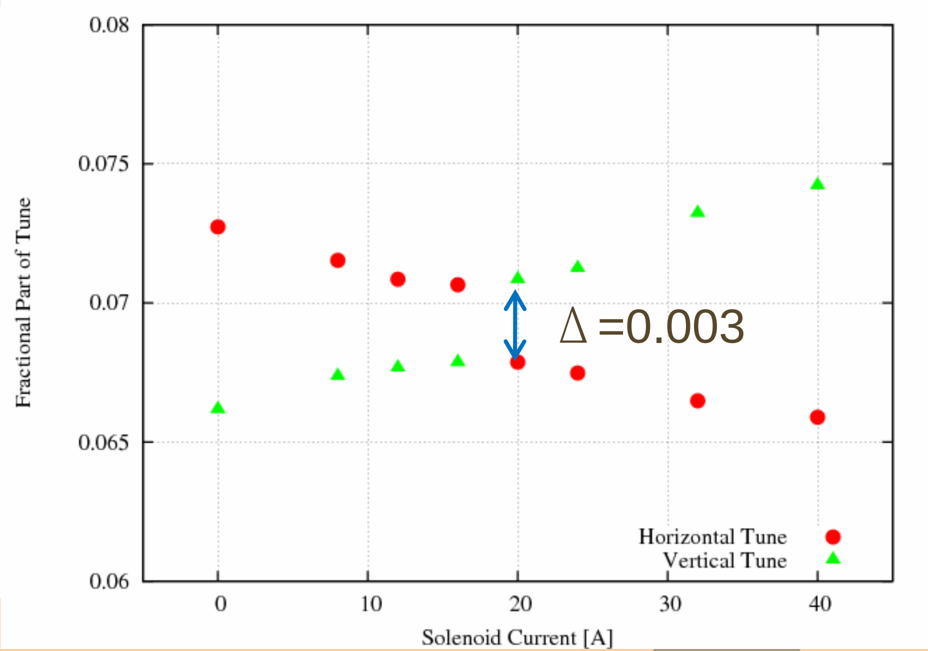
   Capability of pre-cooling by electron beam cooling

   In such a happy situation as realize one dimensional crystal

   →suppression of shear heating by dispersionless lattice

H-V Coupling with a Solenoid Field

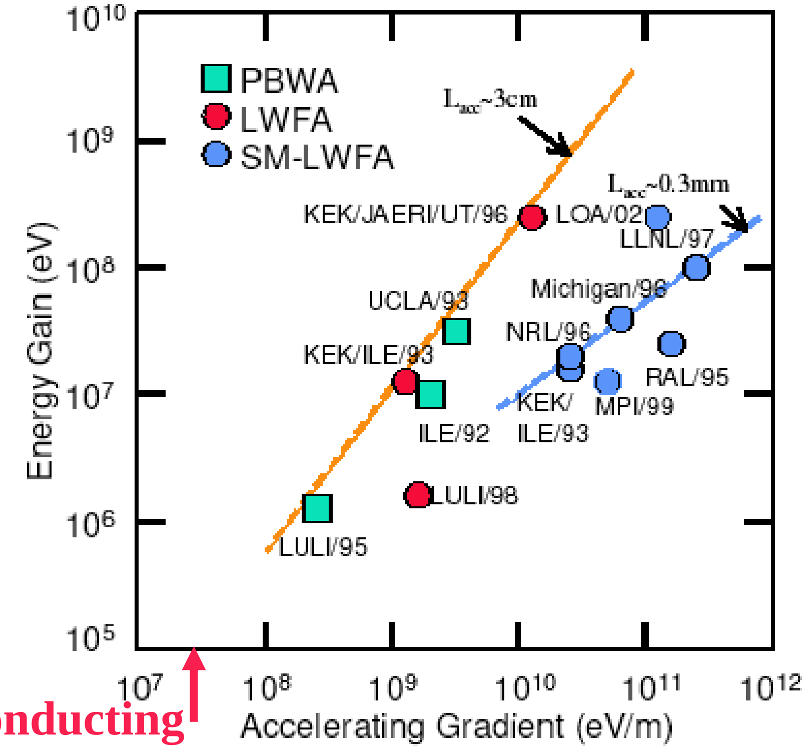




Solenoid Field of Electron Cooler (Effective Length=1.2 m)

Operating Point ~ (2.073, 1.067)

Why Lasers?
—Realization of Very High Field Gradient—



Superconducting RF Cavity

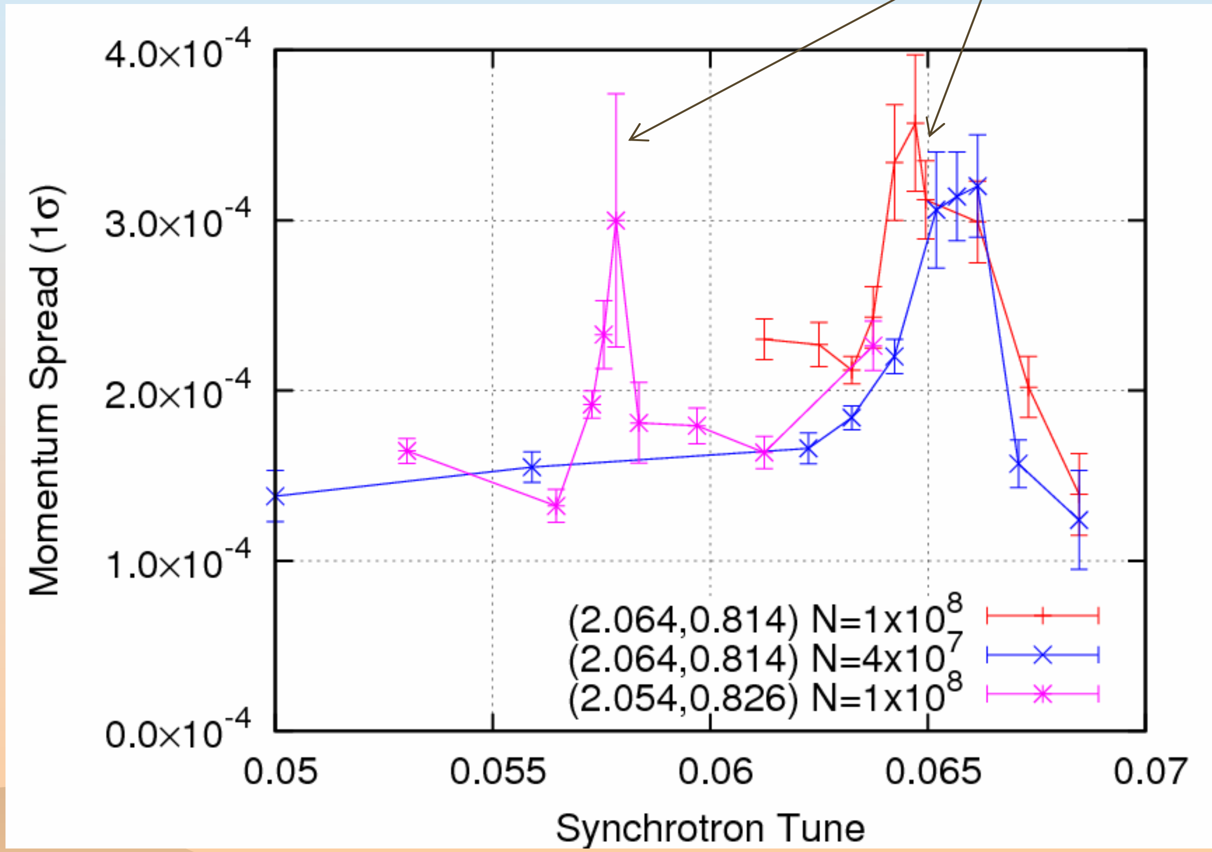
Energy gain and acceleration gradient in Laser-plasma acceleration of electron in last 10 years.

Lecture Note "Oho" by Prof. K. Nakajima

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.

By H. Souda

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

Ion Beam Temperature

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

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

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

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

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

Electron Beam Temperature assuming expansion factor 3)

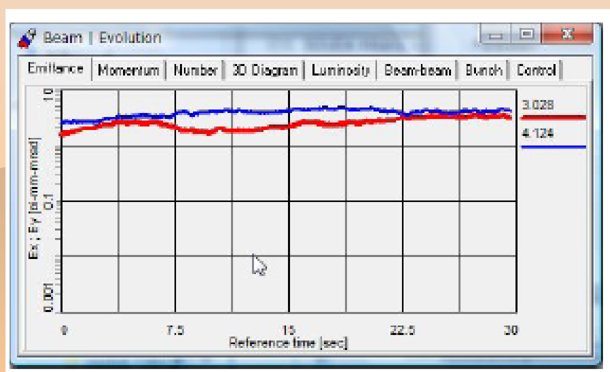
$$k_B T_{e\|} = \frac{(kT_{cath})^2}{m_e c^2 \beta^2 \gamma^2}$$

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

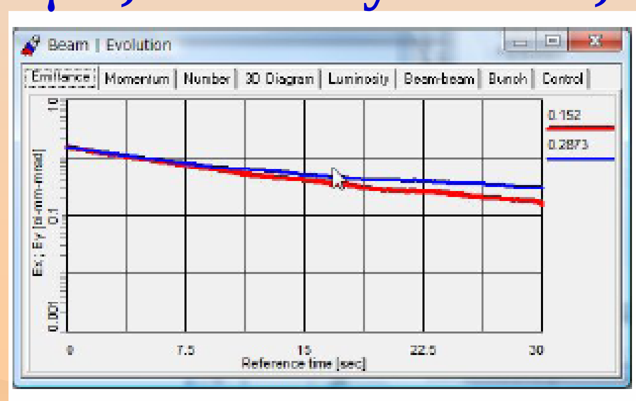
$$T_{e\|} = 5\text{meV} = 58\text{K}$$

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

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

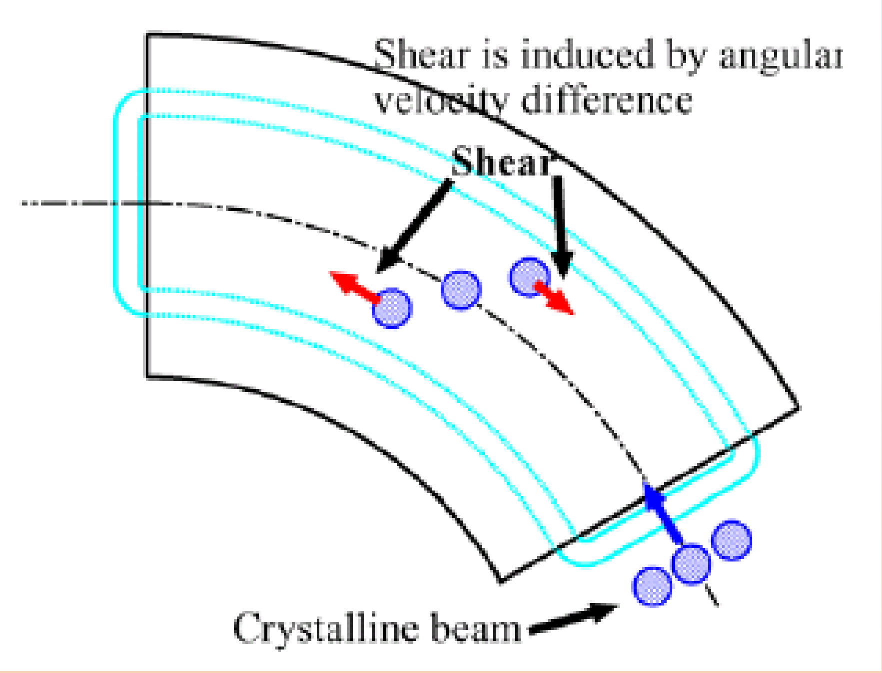


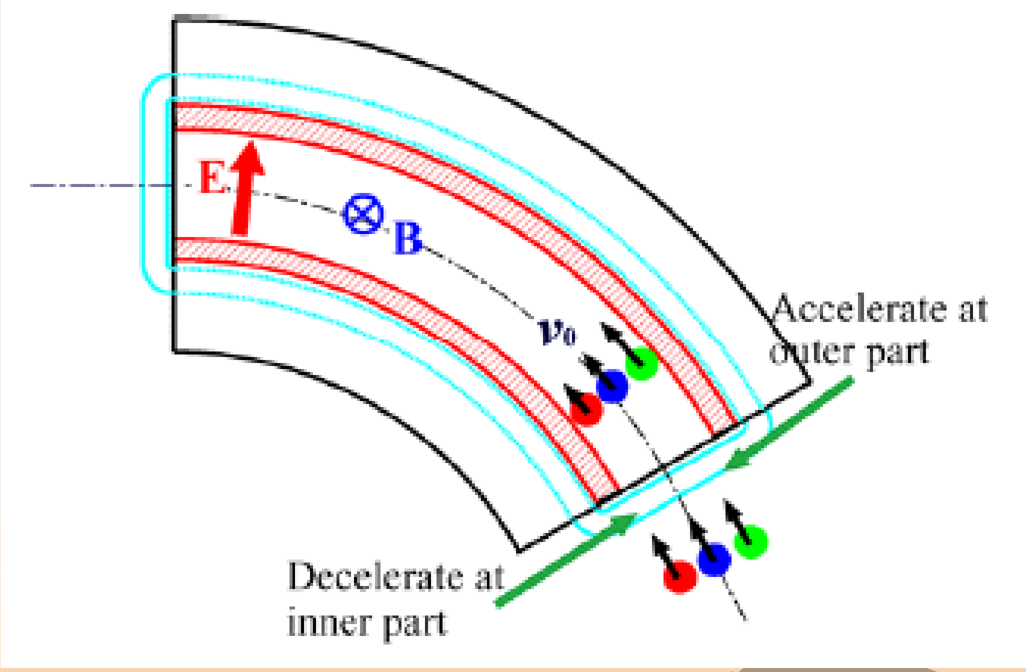
I_e=2μA (extraction 0.9 V)



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

$$\downarrow$$

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

Vacuum Chamber in the Magnet Section (includes the Electrodes)