HIMAC

Ultralow Emittance Beam Production Based on Doppler Laser Cooling and Coupling Resonance

Akira Noda

National Institute of Radiological Sciences

and

M. Nakao, H. Okamoto, K. Osaki,Y. Yuri, H. Souda, H. Tongu, K. Jimbo. M. Grieser, Z. He, A. Smirnov

Contents

1. History of Approach to Low Emittance Beam

Beam Cooling → Reduce Beam Temperature $k_B T_\parallel = m_0 c^2 \beta^2 (\delta p/p)^2$, $k_B T_\perp = 1/2 m_0 c^2 \beta^2 \gamma^2 (y'^2 + z'^2)$

・Motivation of Beam Cooling → Creation of anti- proton beam

→ Creation of Ultra-cold Beam!! (Our Goal)

・Electron Beam Cooling→1D Ordering

・ PALLAS 3D Crystal by Laser Cooling

2. Beam Temperature so far attained by SBRC at S-LSR

・ Doppler Laser Cooling: 1D→3D

40 keV $^{24}Mg^{+}$ Ion Beam Intensity 10^7 => Scraper => 10^4

3. Future Prospect with MD Simulation based on the Experiment

1D Longitudinal String (Bunched), 3D Ordered State (Coasting)

Motive Force of Beam Cooling

– Creation of Good Quality Secondary Beam –

(Anti-proton Beam)

- Electron Cooling (Proposed by G.I. Budker)

→Stochastic Cooling (Proposed by Van der Meer)

Electron Cooling is rather oriented for relatively cooler beam compared with Stochastic Cooling!!

by Late Dr. Dieter Möhl (Proc.of ECOOL84, 293 (1984))

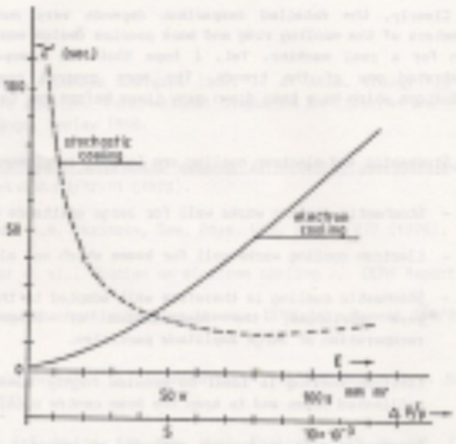


Fig. 2 : Stochastic and electron cooling time as a function of beam emittance.

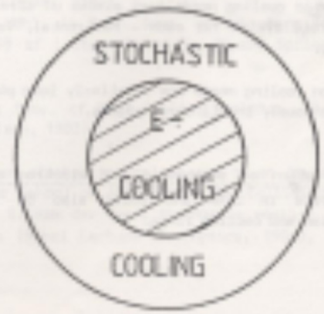


Fig. 3 : Sketch of beam cross-section to indicate regions where one of the two cooling methods is most efficient. The combination of "core cooling" by electrons with "halo cooling" by the stochastic method is capable of taking advantage of both of them.

ESR at GSI, by M. Steck

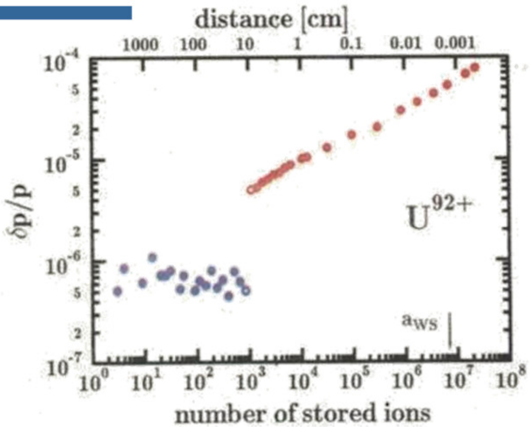


Figure 2. Experimental momentum spreads from Schottky signals vs. number of stored ions in the ESR for electron cooled U^{92+} ions at 240 MeV/u. a_{WS} indicates the Wigner-Seitz radius of eq.(3). (after ref. [9])

CRYRING at Stockholm, by H. Danared

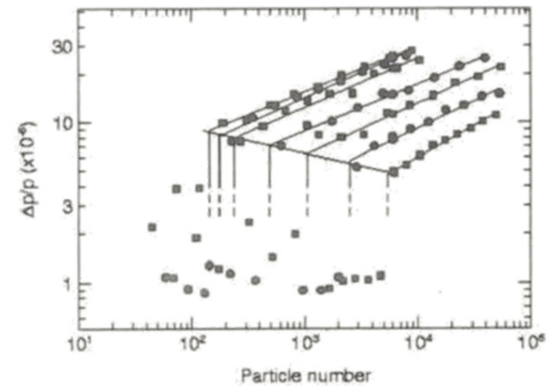


Fig. 5: Relative momentum spread as a function of particle number for the lowest seven electron densities represented in Fig. 2. The density increases from the upper left to the lower right. For each density, a line is fitted to the data points. A line is also drawn through the points corresponding to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

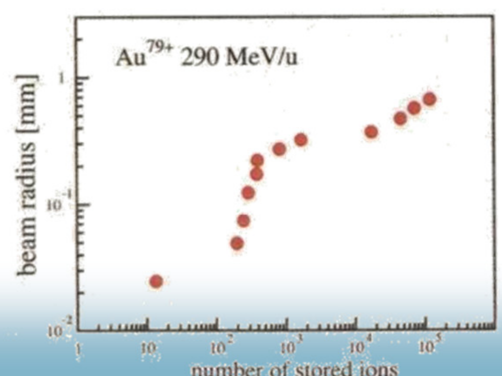


Figure 3. Beam radius measured with a beam scraper vs. number of stored ions in the ESR for electron cooled Au^{79+} ions at 290 MeV/u (from ref. [10]).

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

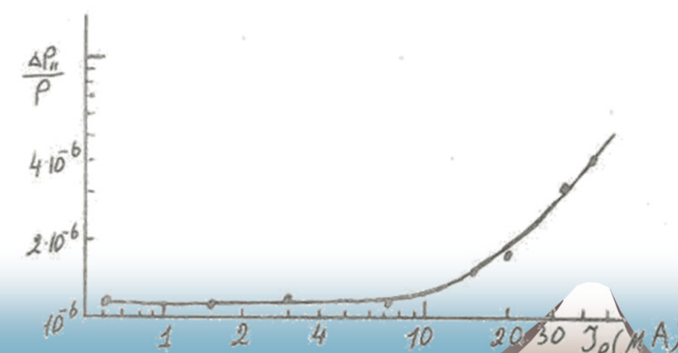
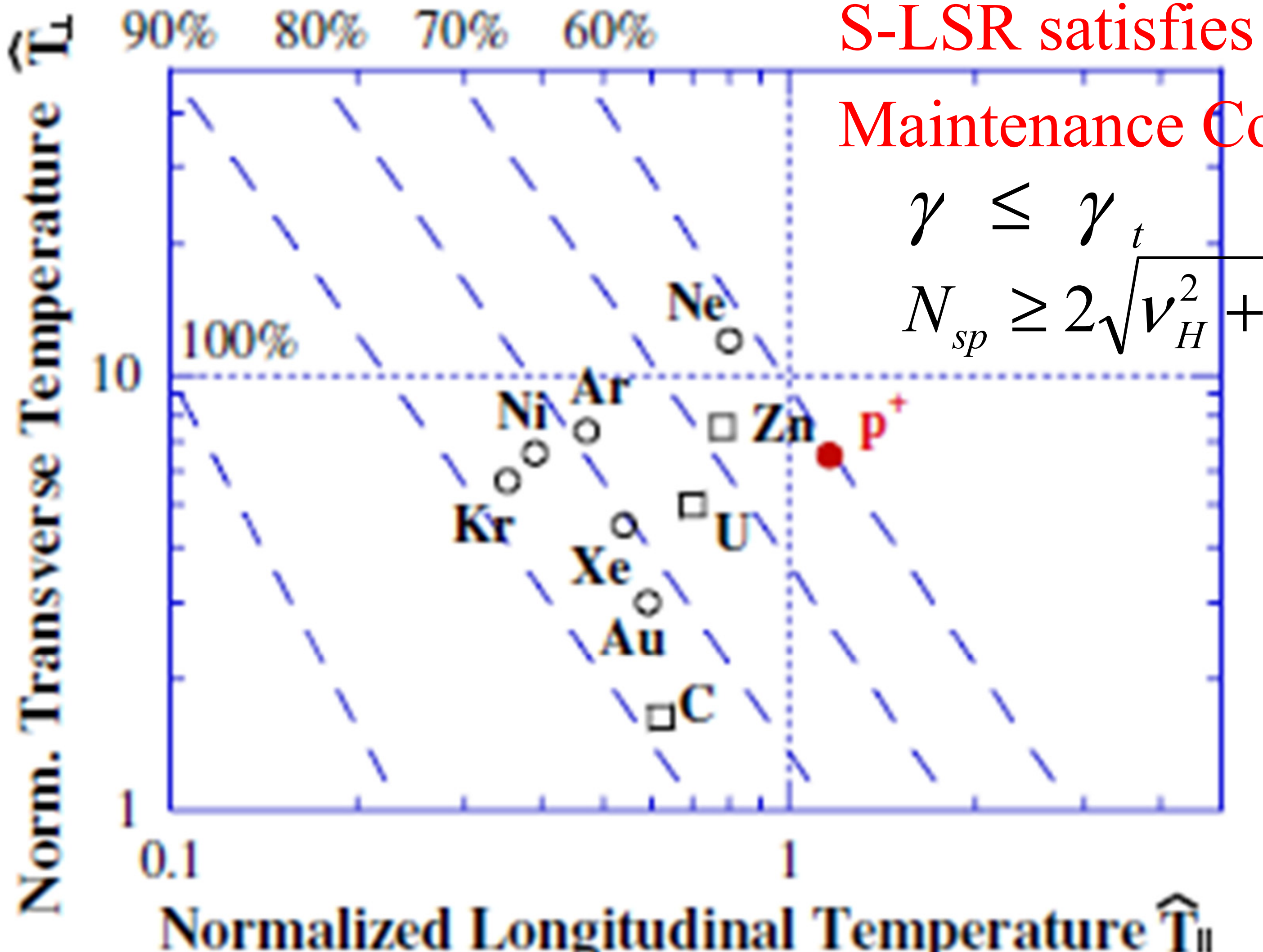


Fig. 6. The momentum spread of proton beam versus current J_p.

Reflection Probability of Ions made Phase Transition



S-LSR satisfies

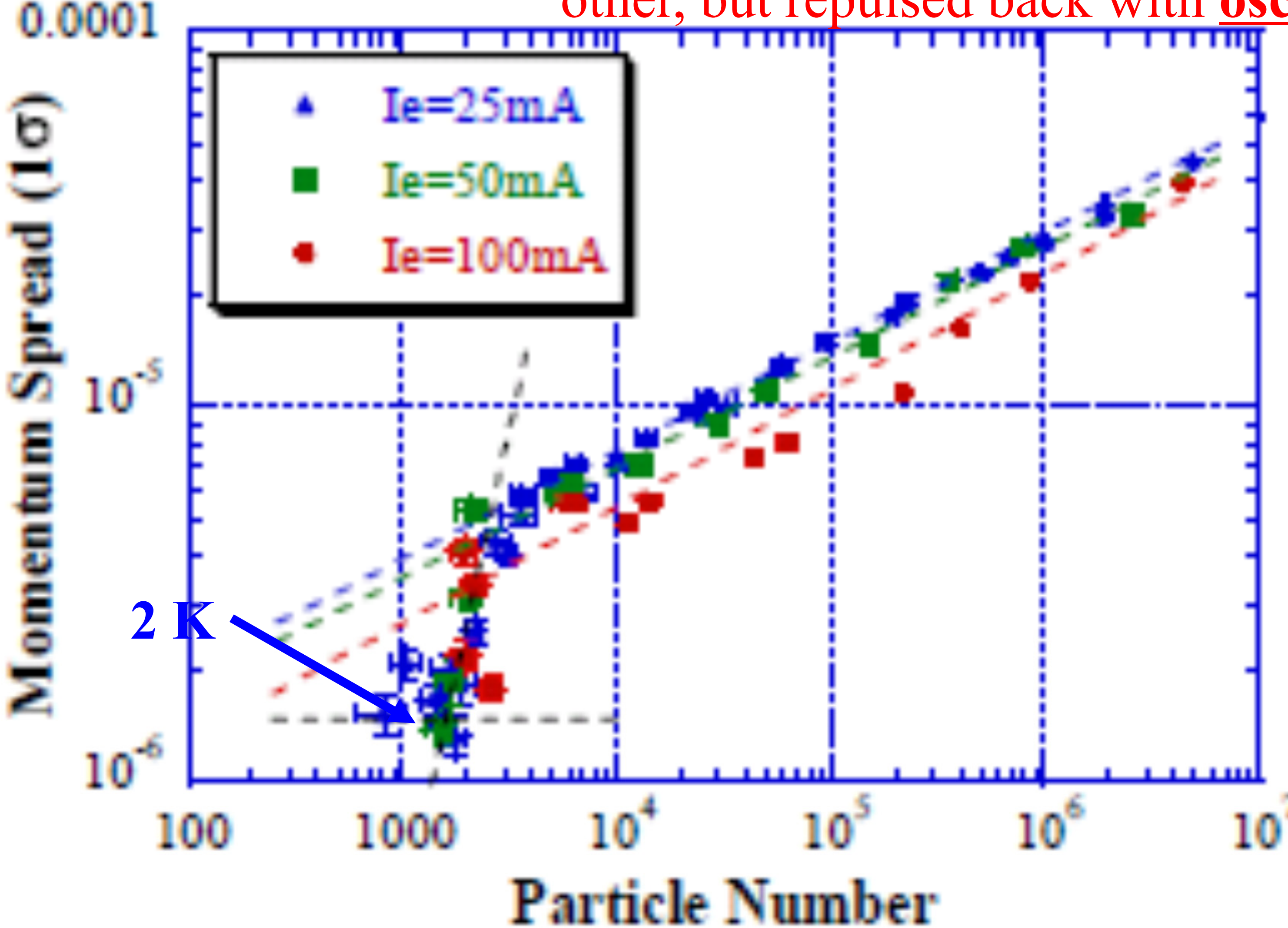
Maintenance Condition

$$\gamma \leq \gamma_t$$

$$N_{sp} \geq 2\sqrt{\nu_H^2 + \nu_V^2}$$

Phase Transition to 1D Ordered State

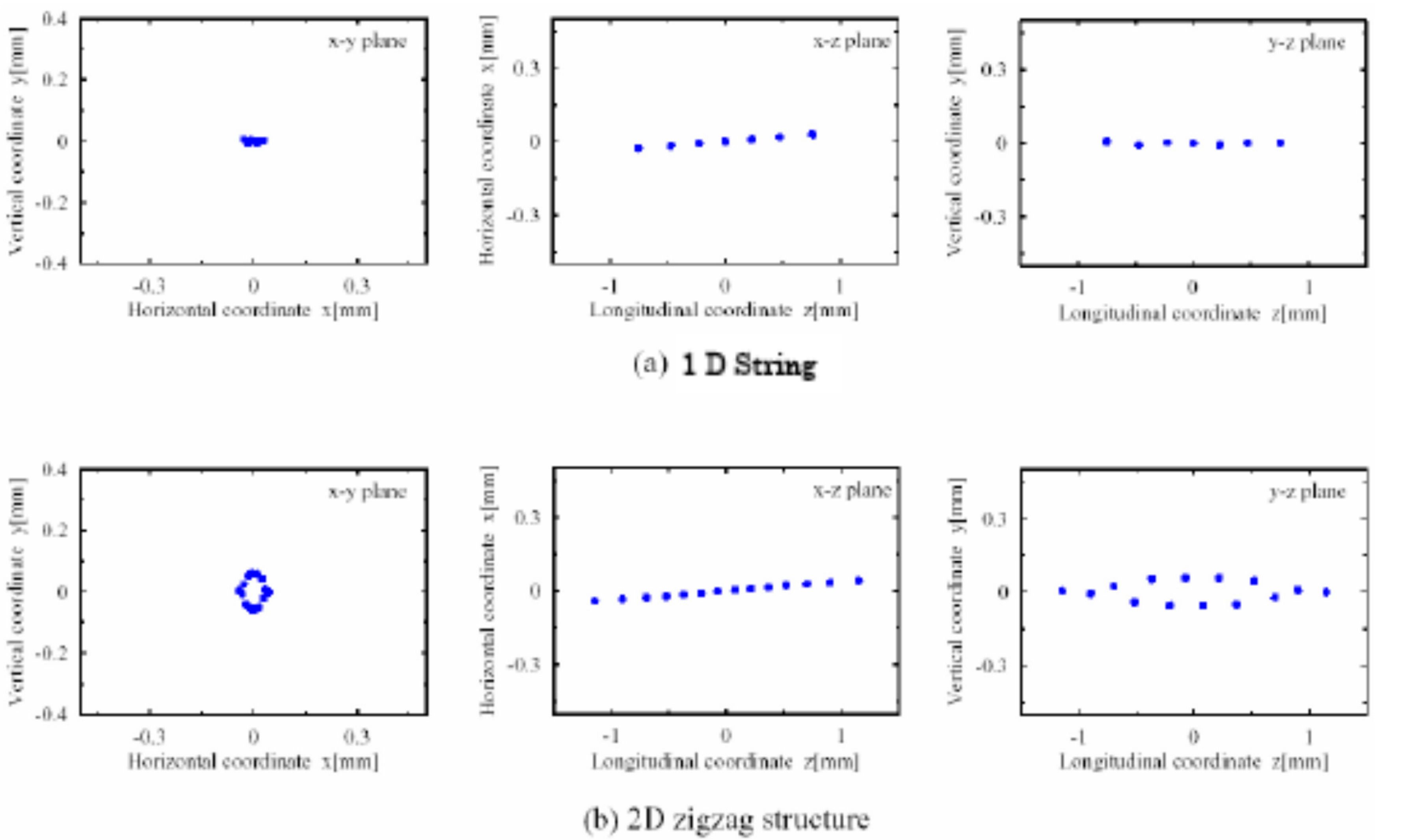
Adjacent particles never take over each other, but repulsed back with **oscillation**



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

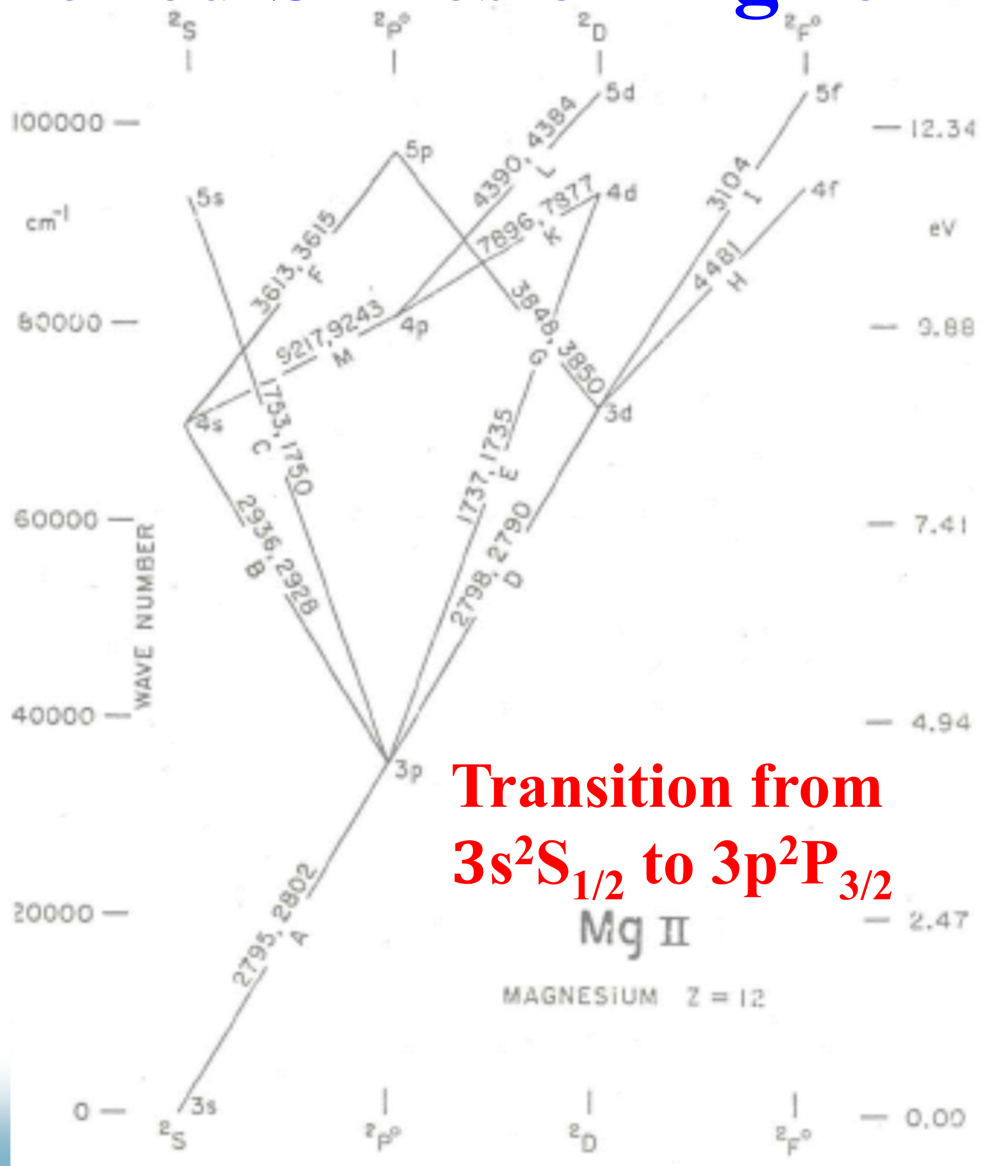
Simulation by H. Okamoto et al.

Expectation from Simulation



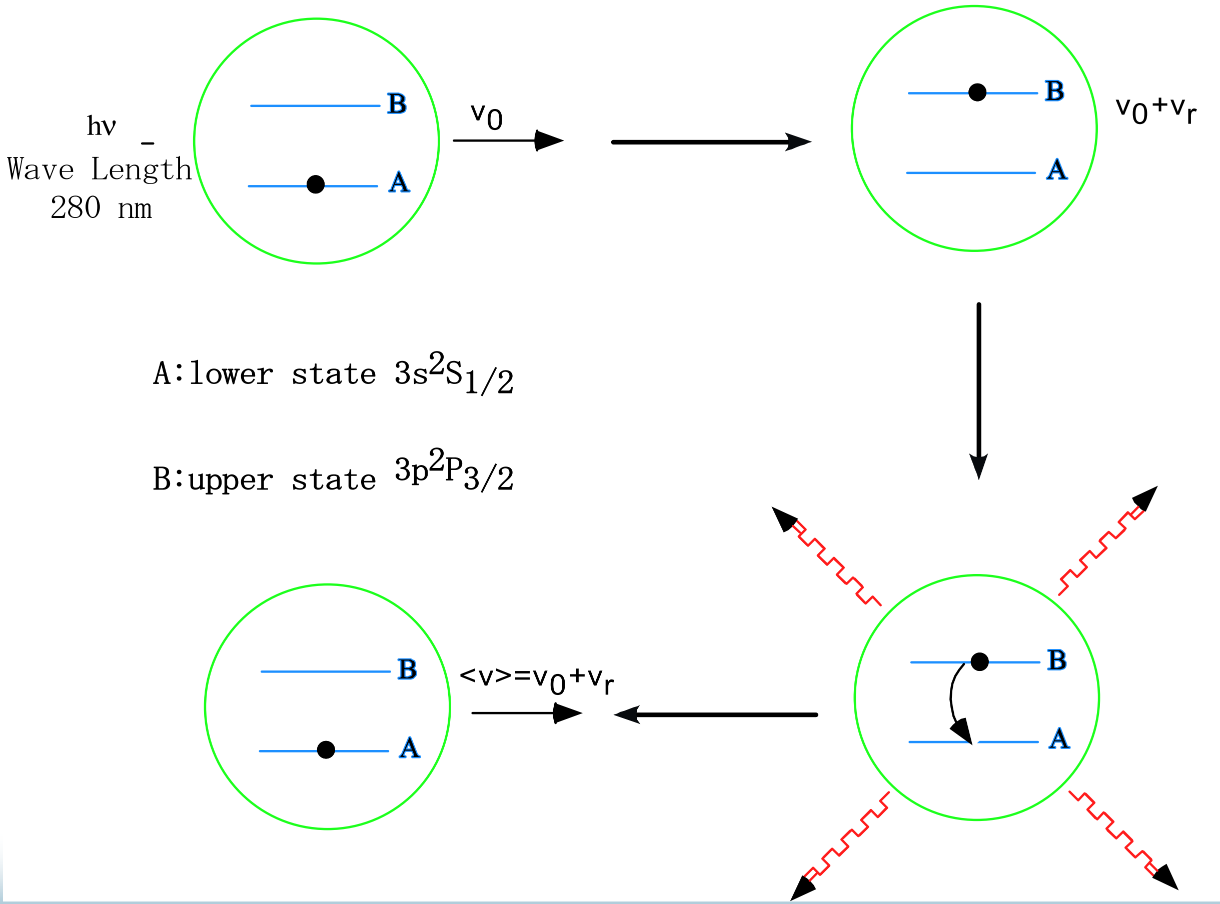
Doppler Laser Cooling of Ion Beam Circulating in a Storage Ring

Excited States of Mg Ion



Transition from $3s^2S_{1/2}$ to $3p^2P_{3/2}$

Principle of Laser Cooling (Longitudinal)



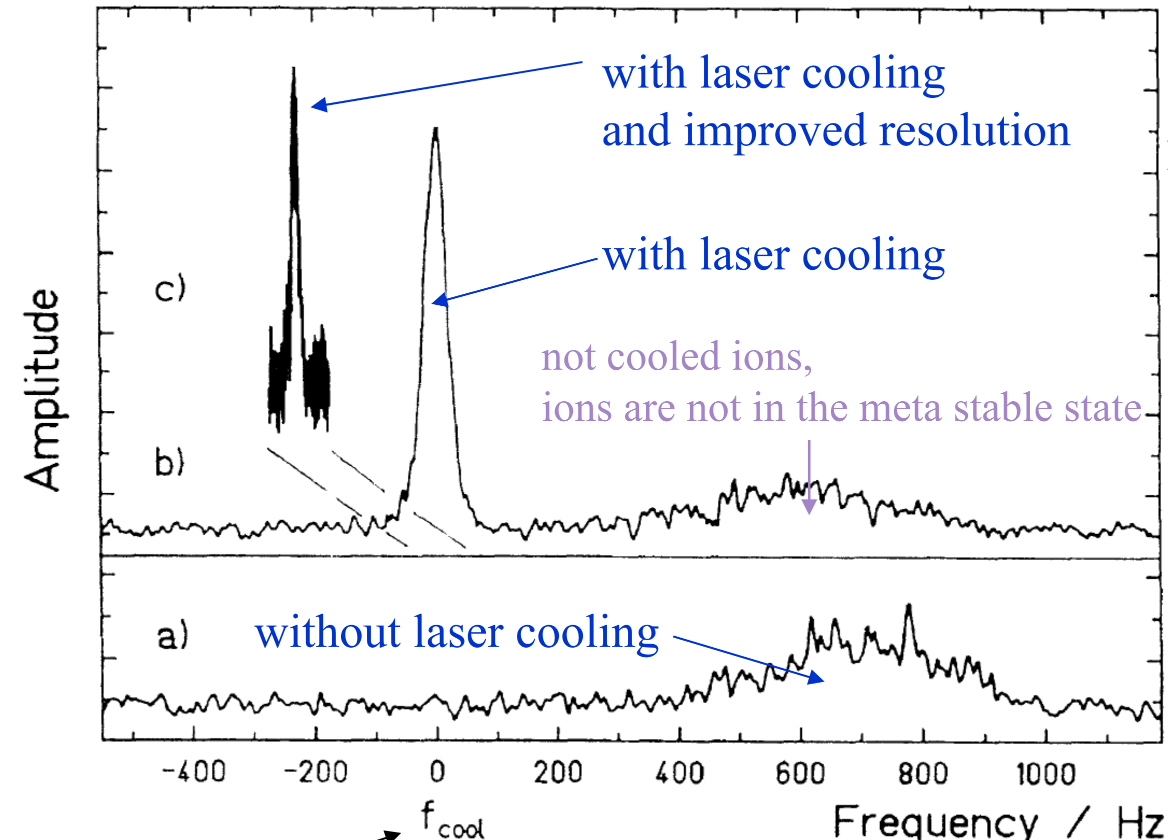
Borrowed from Dr. M. Grieser

First laser cooling of ions in a storage ring

S. Schröder et. al. physical review letters, volume 64 No. 24 (1990) p. 2901-2904

Experiments done at **TSR** storage ring with **$^{7}Li^{+}$ (E=13.4 MeV)** ions.

Schottky noise signals with and with out laser cooling



Only effective in the beam direction (1D)

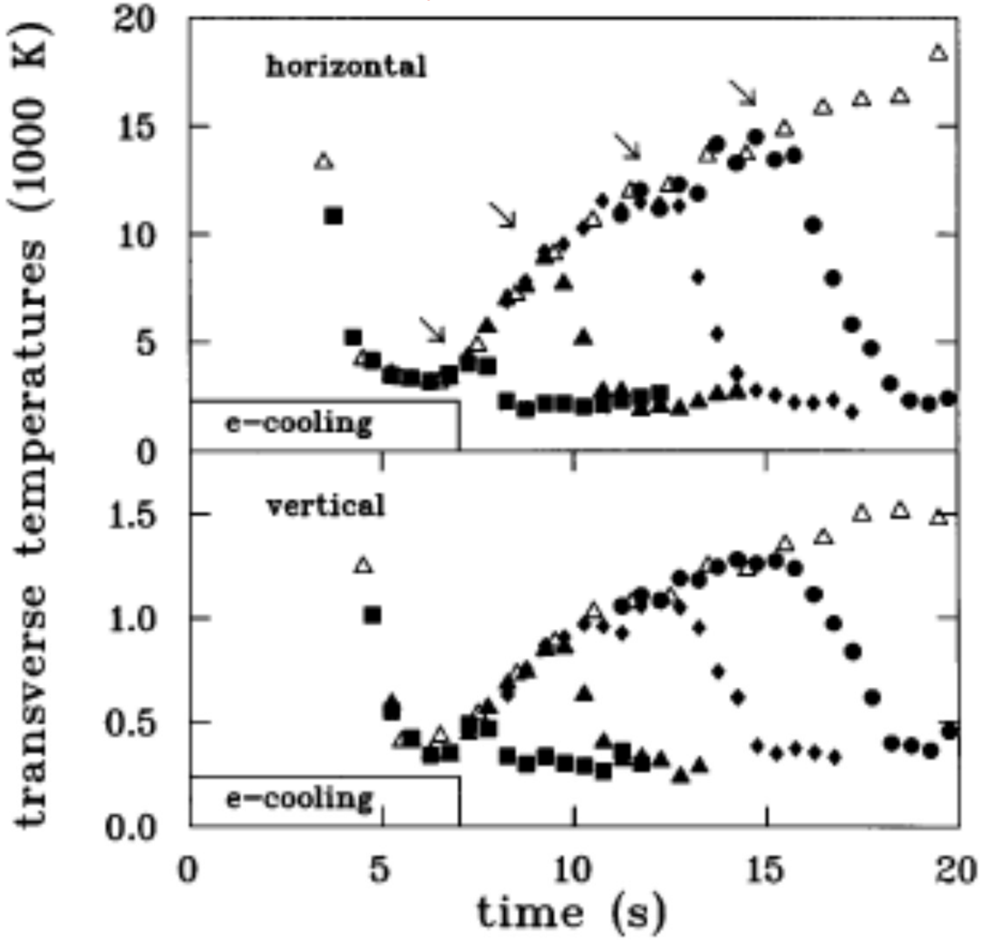
f_{cool}=6.210 MHz

final longitudinal temperature: $T_{\|} \leq 2.9$ K

Transverse Laser Cooling attained at TSR

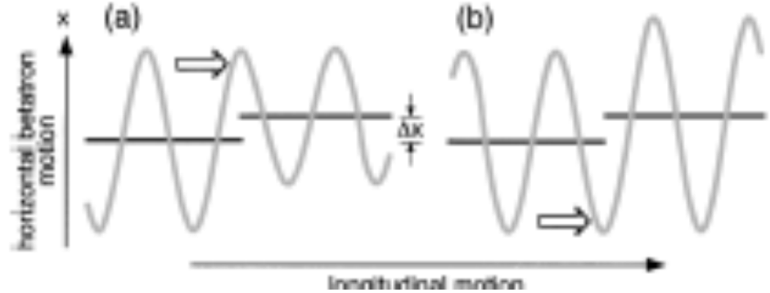
Utilize IBS

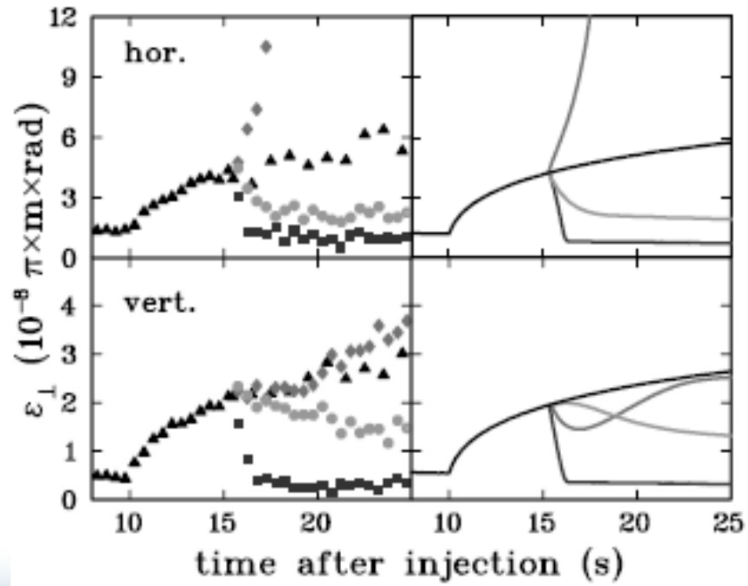
H.J. Miesner et al., Phys. Rev. Lett. 77, 623 (1996)



Dispersive Coupling

I. Lauer et al., Phys. Rev. Lett. 81, 2052 (1998)





Longitudinal :15 K, H: ~4000 K, V: 500 K

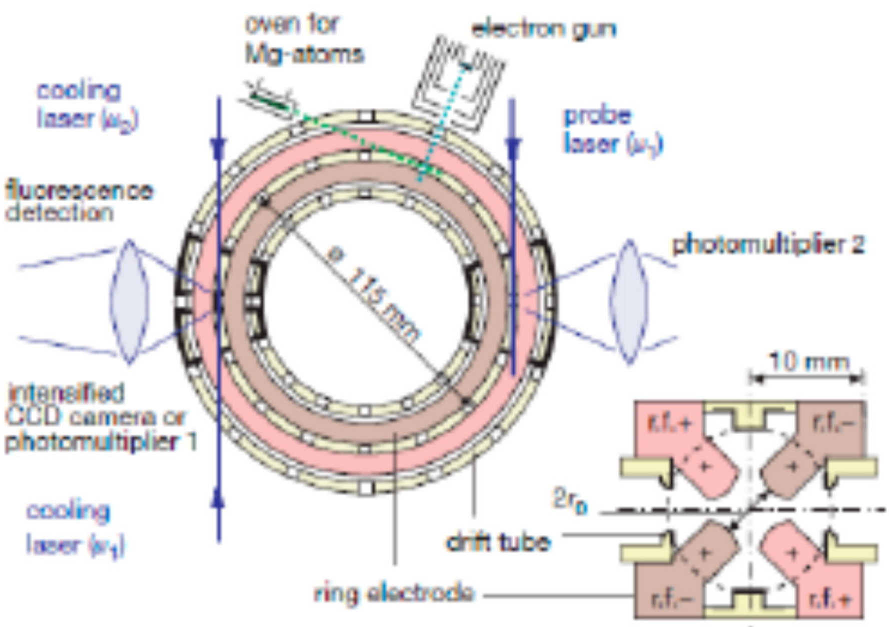
ASTRID Longitudinal :2.5 K, H: K17 K, V: 21 K

Intensity 7 x 10^5, 100 keV, Mg Ion

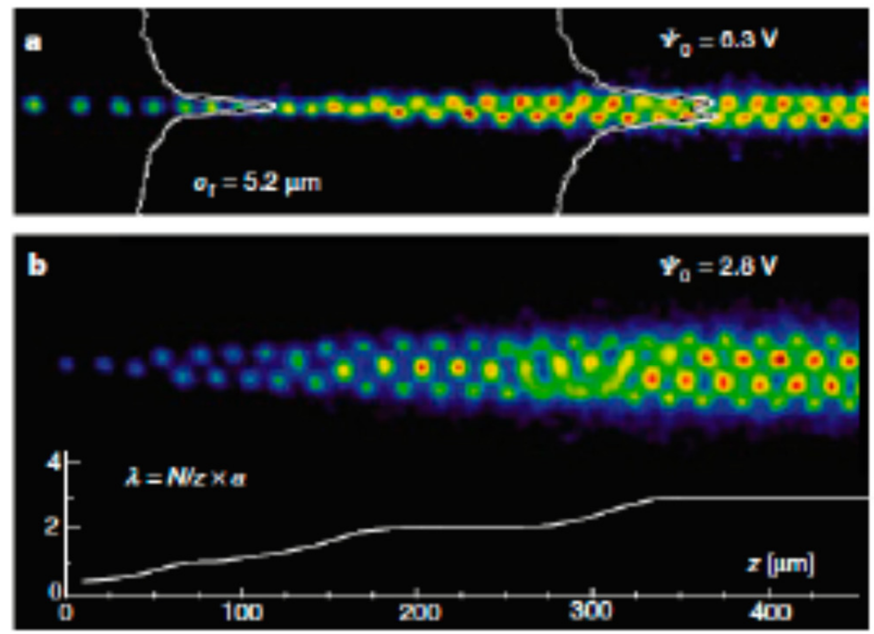
Longitudinal : few tens K, H: ~500 K, V: ~150 K

Crystalline Beam in Circular RFQ, PALLAS

T. Schatz, U. Schramm, D. Habs:, Nature, 412, 717 (2001)



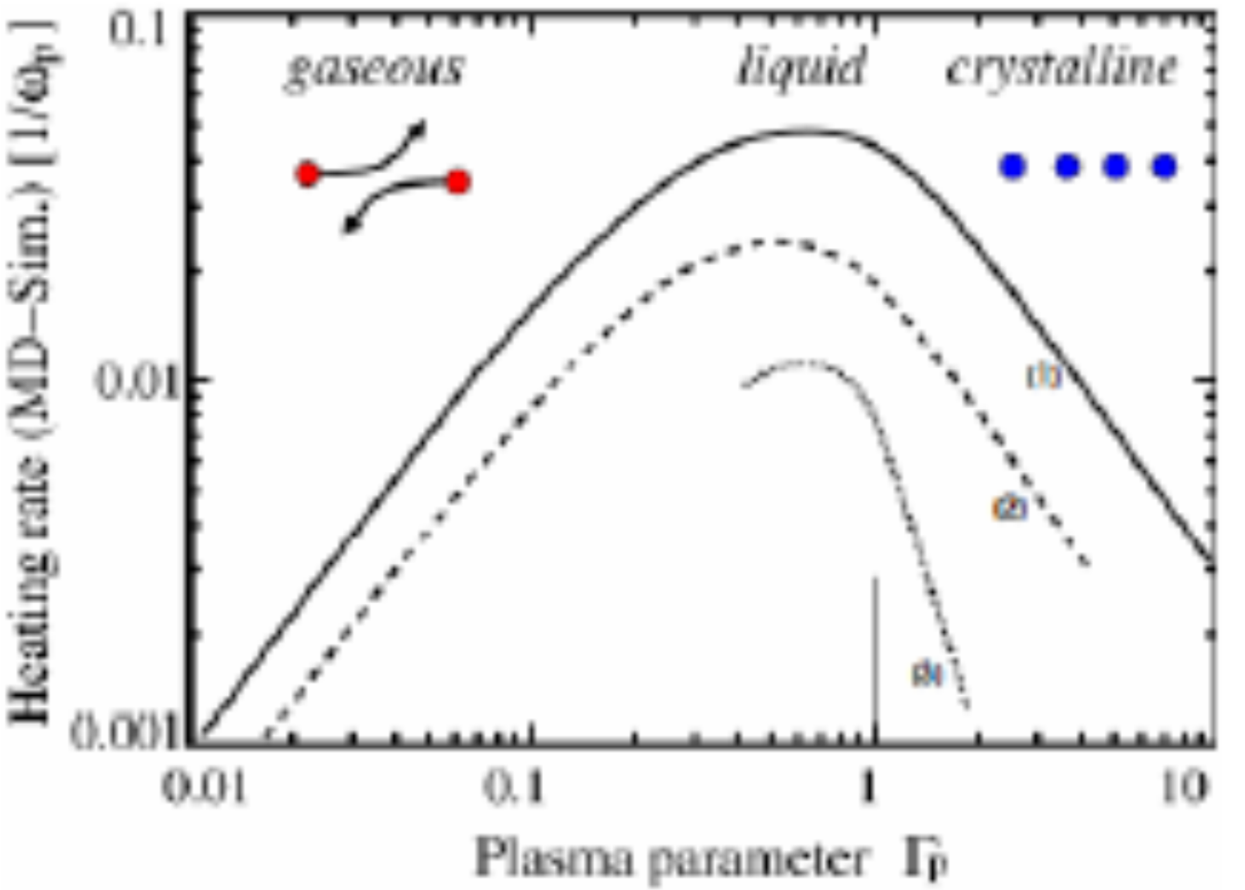
Structure of Circular RFQ, PALLAS



Images of ion crystals at rest in PALLAS

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

Plasma Parameter Dependence of Heating Rate



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

(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

Compact Cooler Ring S-LSR

－Circumference 22.56m

－Straight Section Length 1.86m

E-cooling modes

- Protons 7MeV (Ee=3.8keV)

Laser cooling

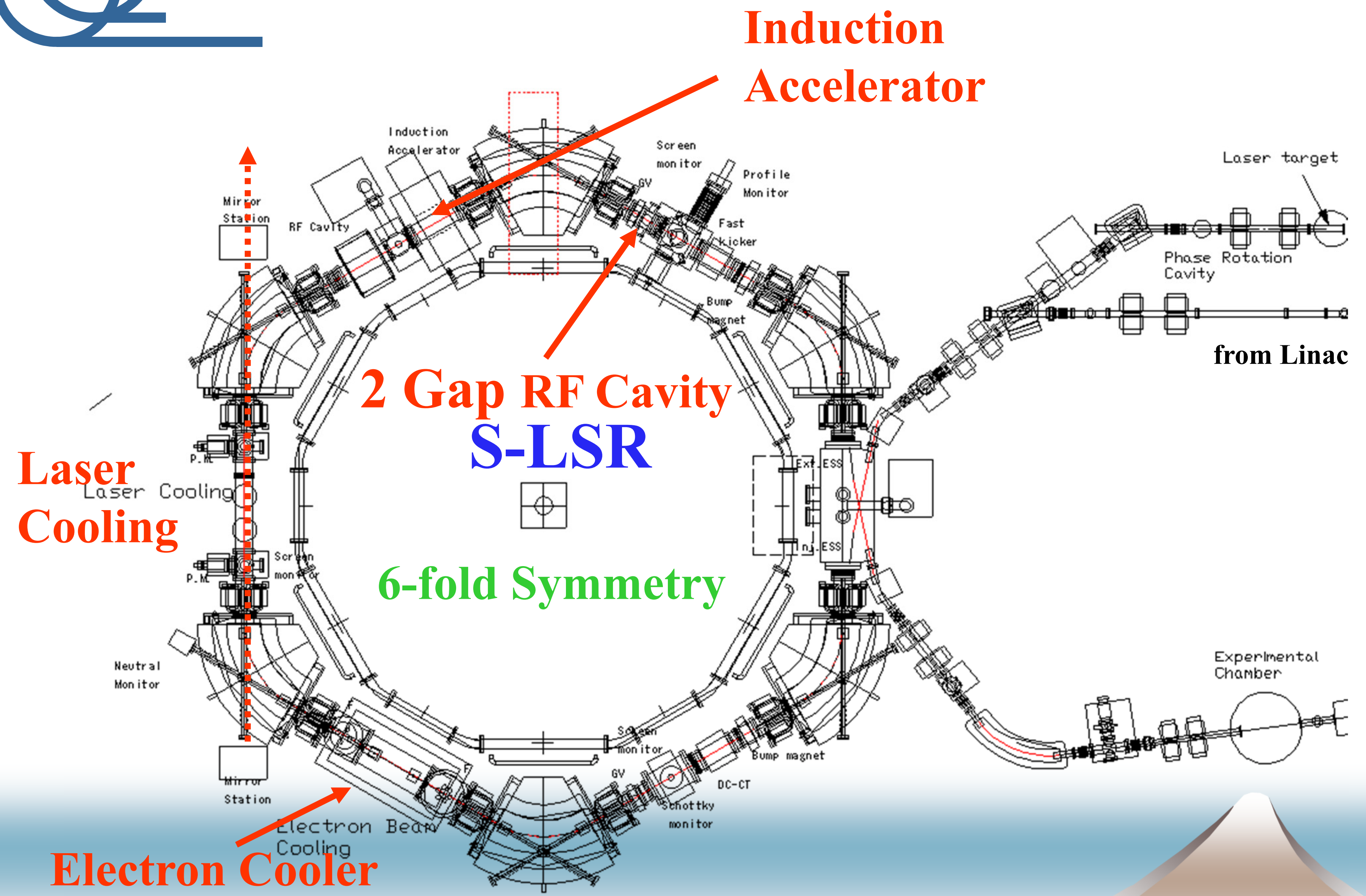
- $^{24}Mg^{+}$ 40 keV (l=282 nm)

Operation: Since October, 2005 to March, 2013, Now in rest

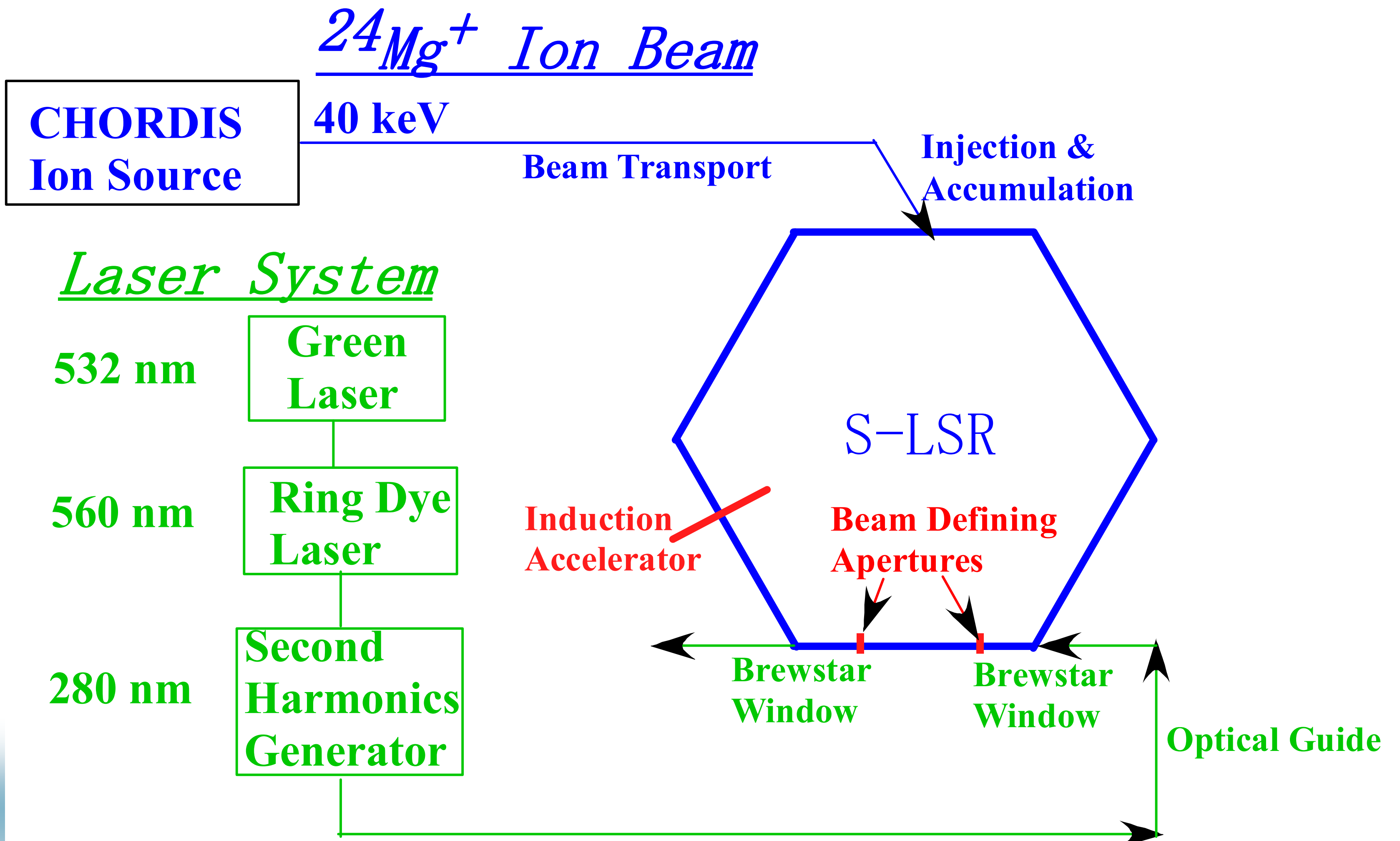
Main Parameters of S-LSR

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): EC
	2.068(H), 1.105, 1.070 (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

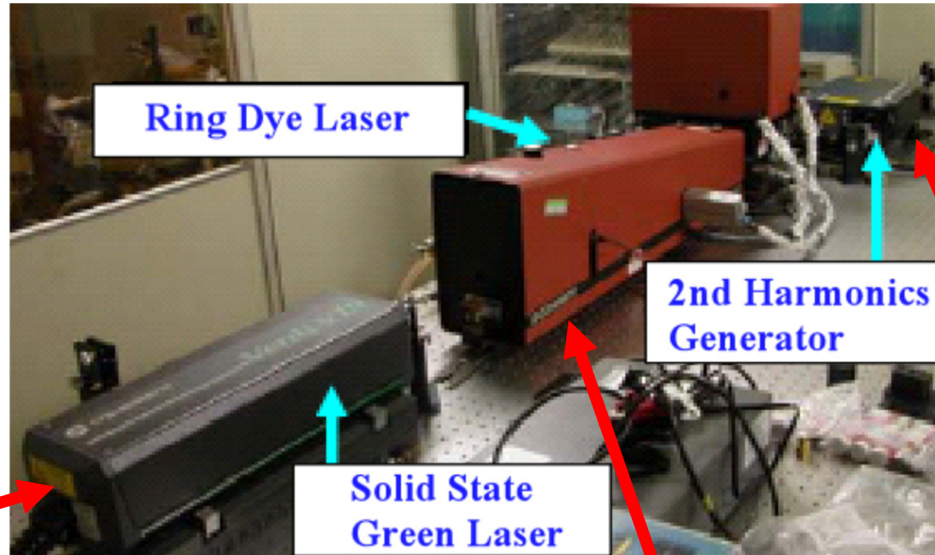
Ring Layout

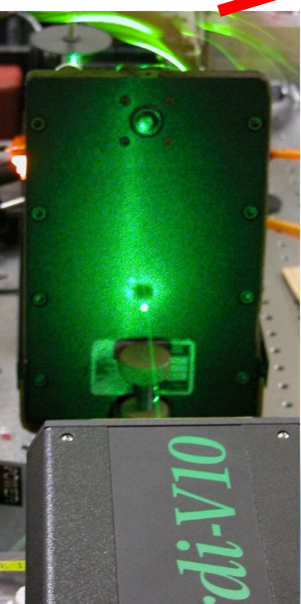

Induction Accelerator
Induction Accelerator
Screen monitor
Profile Monitor
Laser target
Mirror Station
RF Cavity
GV
Fast kicker
Phase Rotation Cavity
Bump magnet
from Linac
2 Gap RF Cavity
S-LSR
Laser Cooling
Laser Cooling
P.M.
Ext.ESS
Inj.ESS
Screen monitor
6-fold Symmetry
Neutral Monitor
Experimental Chamber
Screen monitor
Bump magnet
GV
DC-CT
Mirror Station
Schottky monitor
Electron Beam Cooling
Electron Cooler

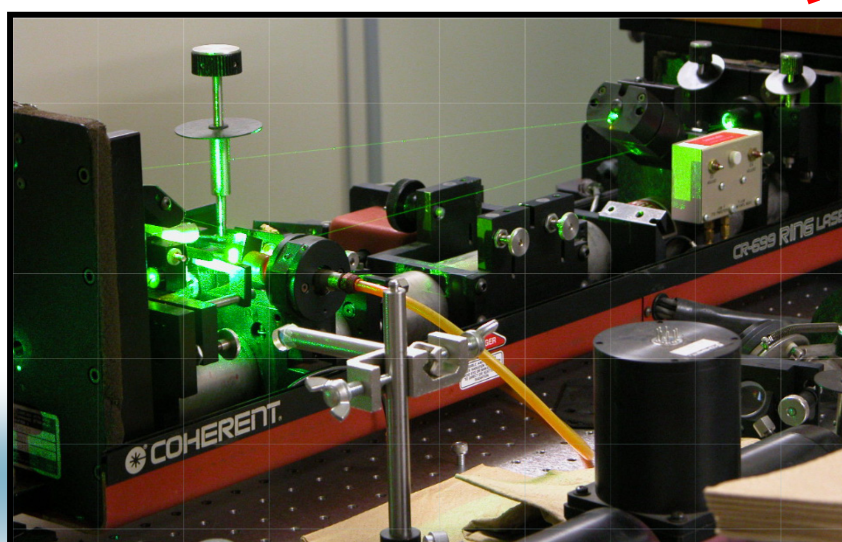
Block Diagram of Laser Cooling at S-LSR

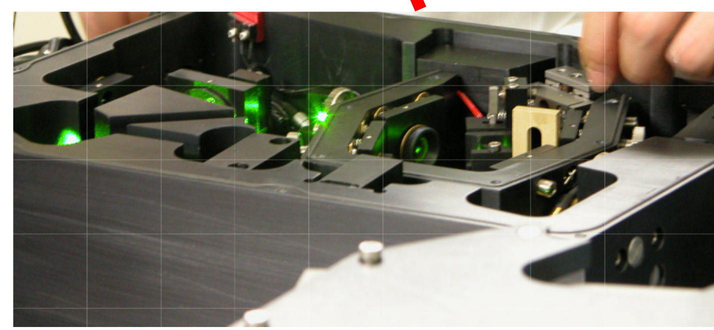


Laser System for Cooling





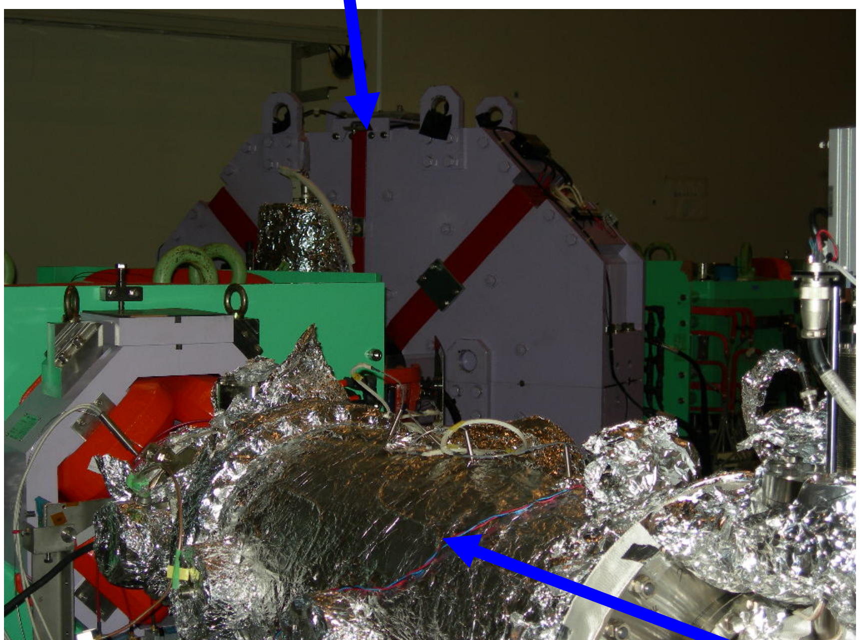


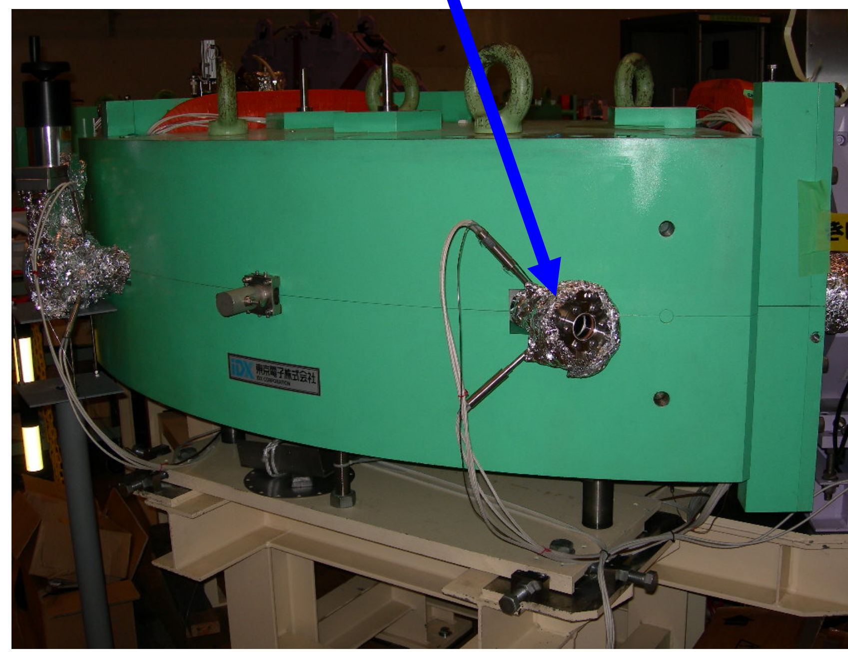


Laser Cooling Section of S-LSR

Induction Accelerator

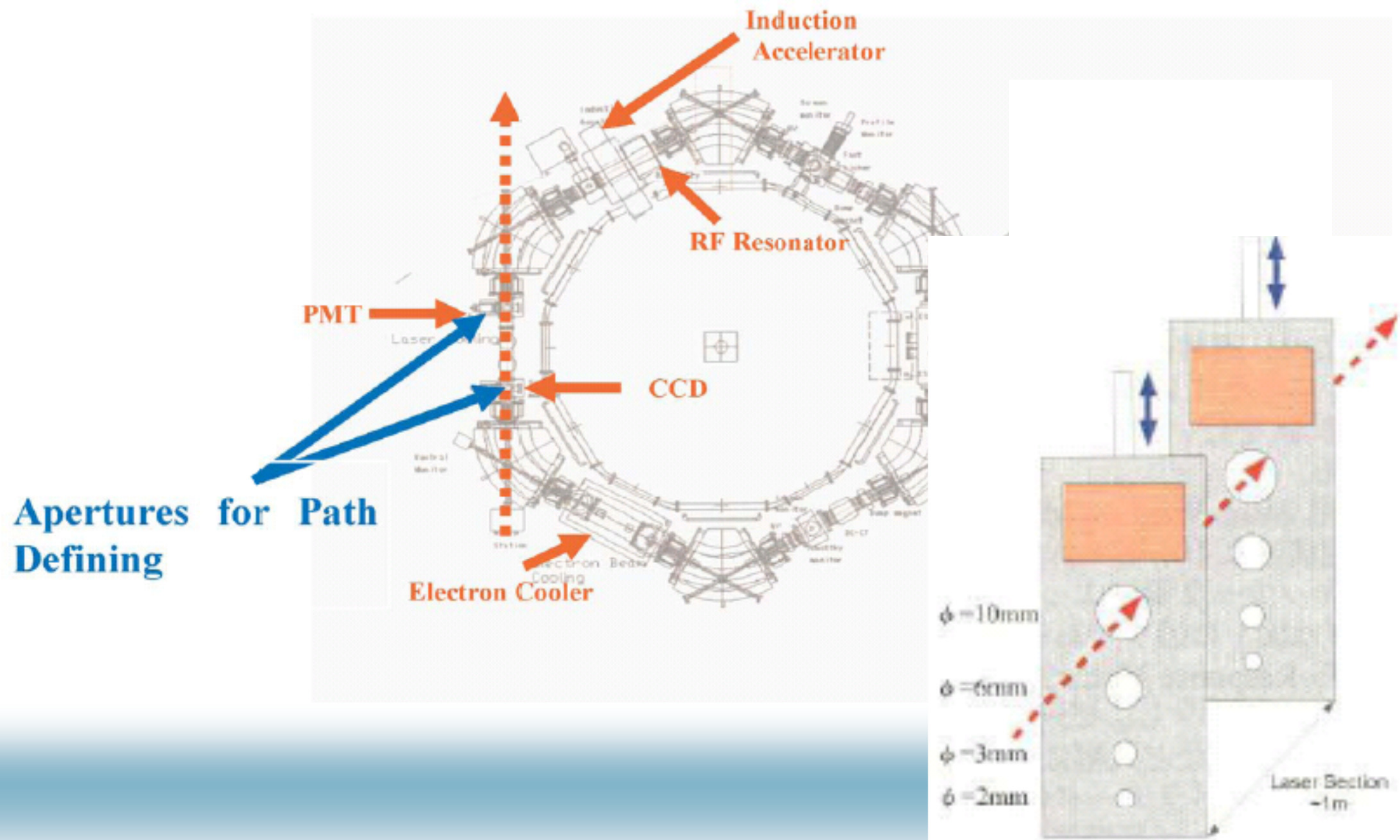
Window for Laser port
(with Brewstar Angle)





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

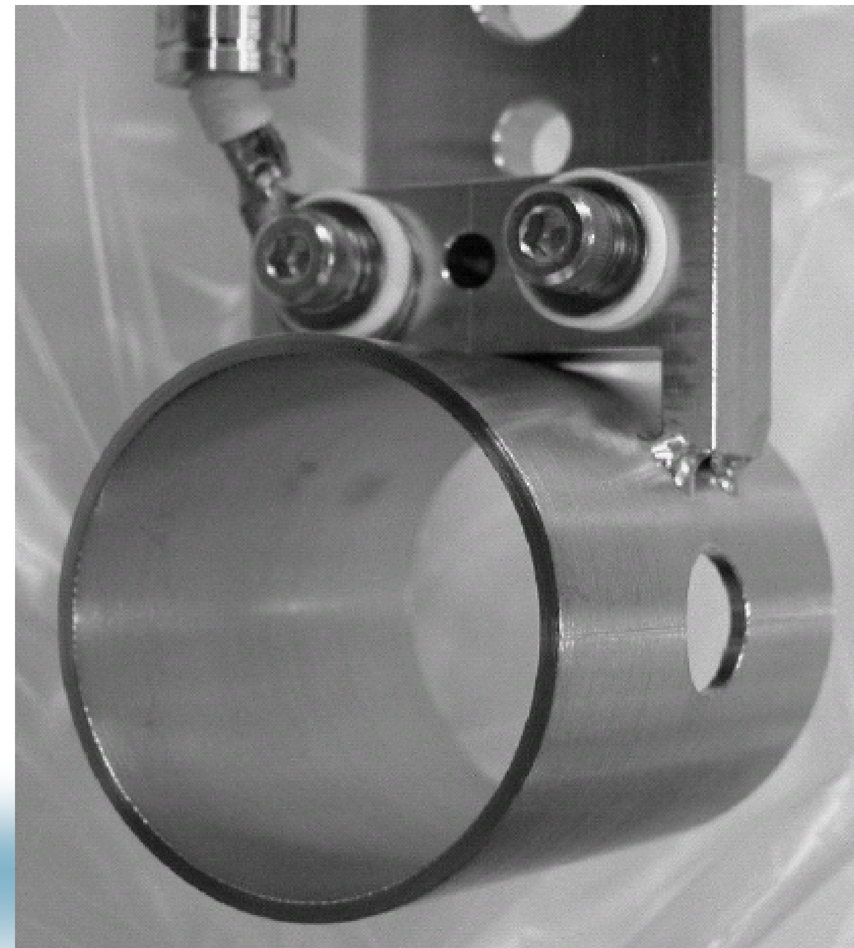
Overlapping of Ion and Laser Beams



T. Ishikawa, Master Thesis, Kyoto Univ. (2008)

Post Acceleration Tube (PAT)

-Energy Sweep is applied for Distribution Measurement-

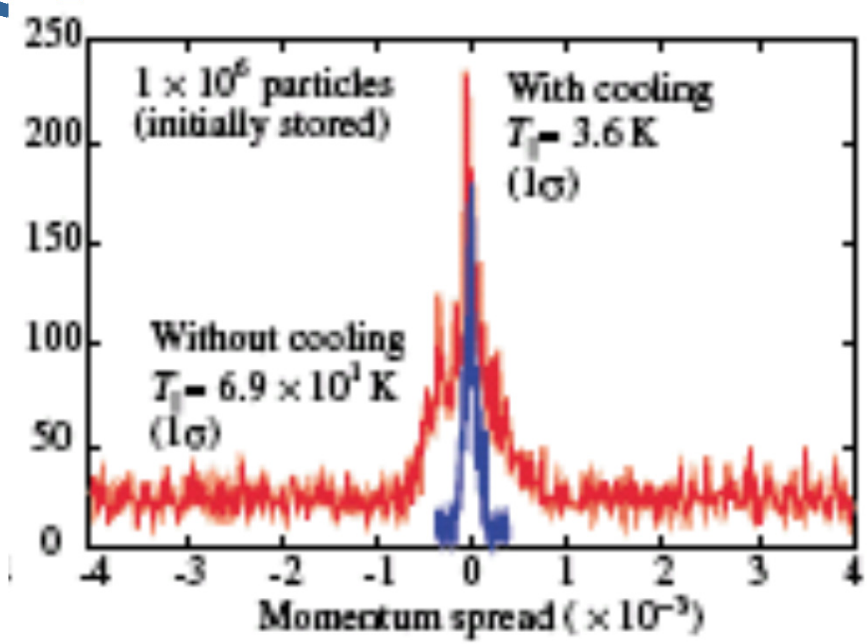


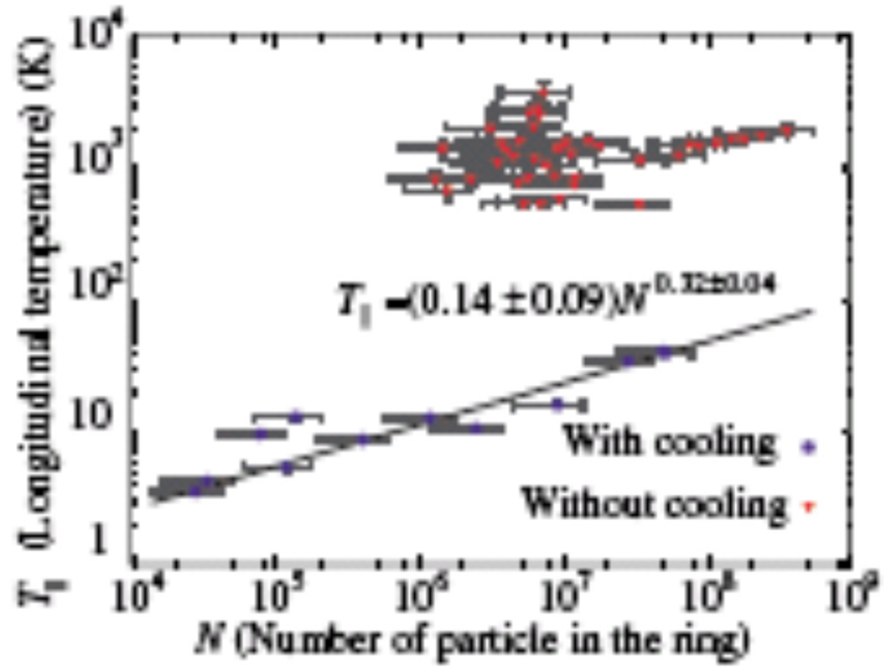
Specification of PAT

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

M. Tanabe et al., Appl. Phys. Express 1, 028001 (2008)

Laser Cooling of Coasting Beam at S-LSR





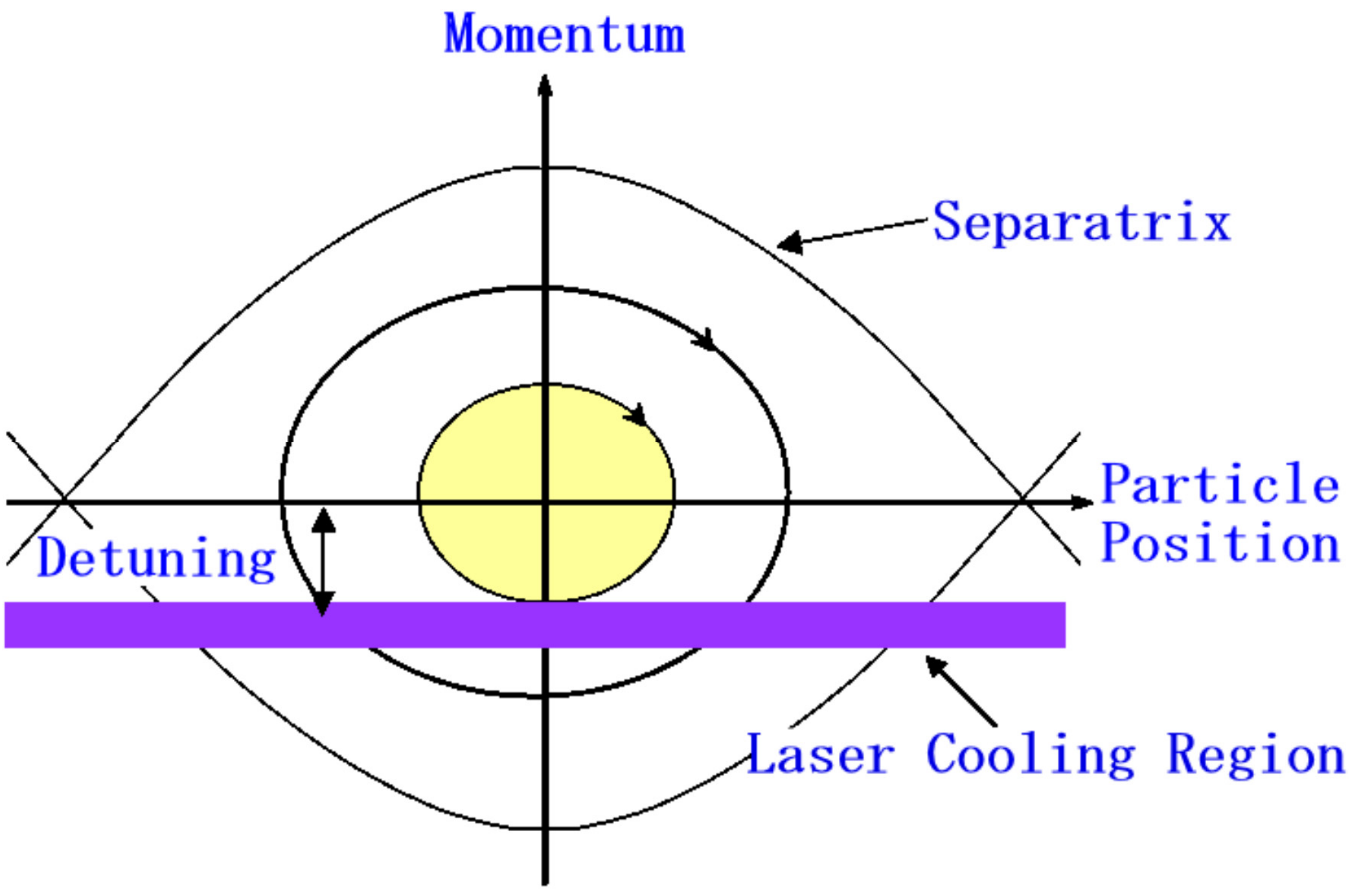
$$k_B T_{\mathrm{L}} = m v_0^2 \left(\frac{\Delta p}{p} \right)^2$$

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

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

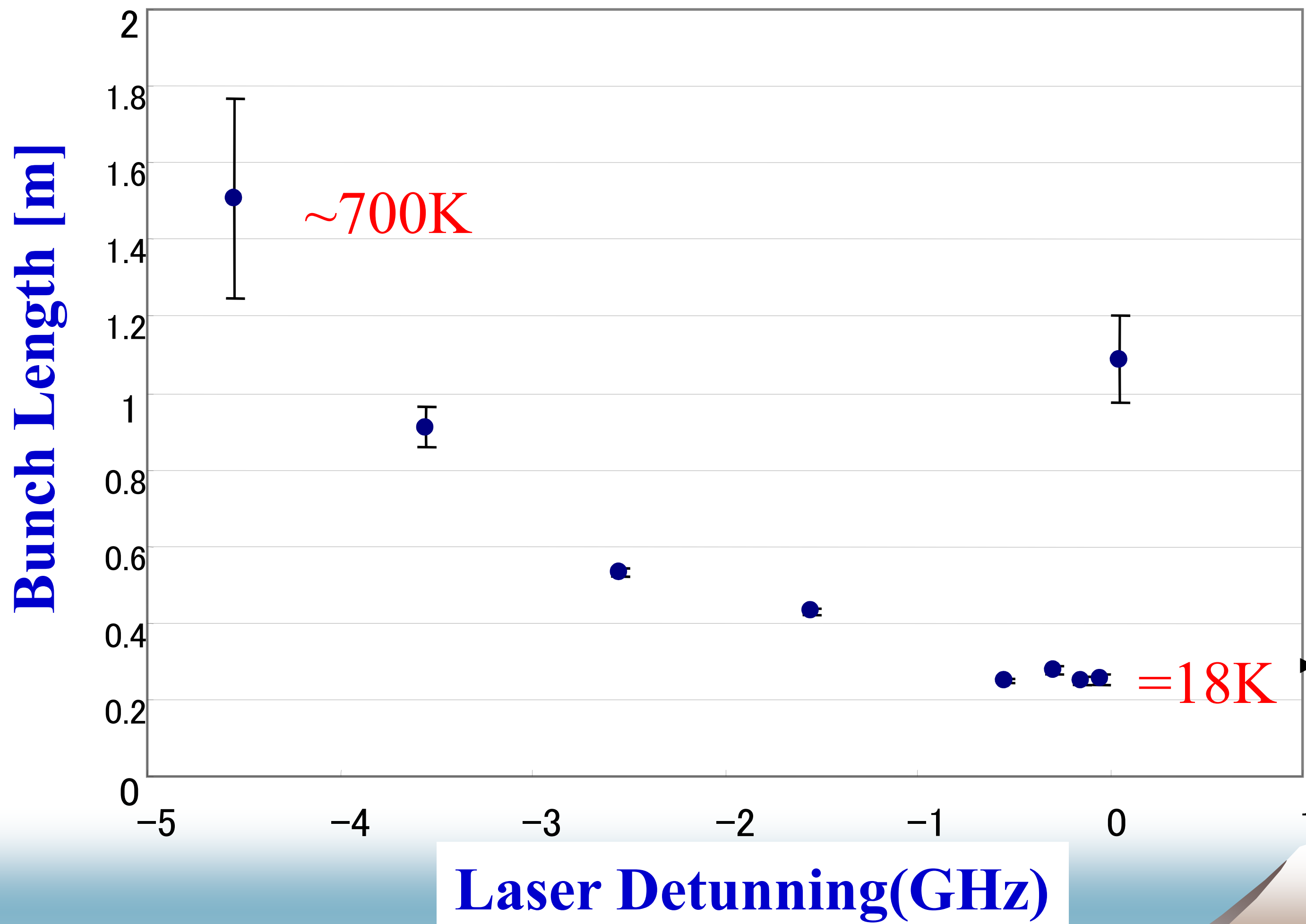
$$\Lambda_{IBS} \propto N \Big/ T_H T_V \sqrt{T_L} \longrightarrow T_L \propto N^{0.4}$$

Bunched Beam Cooling



Result of Bunched Beam Cooling

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



H. Okamoto, A.M. Sessler and D. Möhl, Phys. Rev. Lett. 74, 397 (1994)

Synchro-Betatron Resonance Coupling (SBRC) Scheme

$$H = \underbrace{\frac{1}{2}(p_x^2 + \kappa_x^2 x^2) + \frac{1}{2}(p_x^2 + \kappa_y^2 y^2)}_{\text{Betatron oscillation}} + \underbrace{\frac{1}{2}(p_x^2 + \kappa_z^2 z^2)}_{\text{Synchrotron oscillation (laser cooled)}} + \psi_c$$

Controllable coupling potential

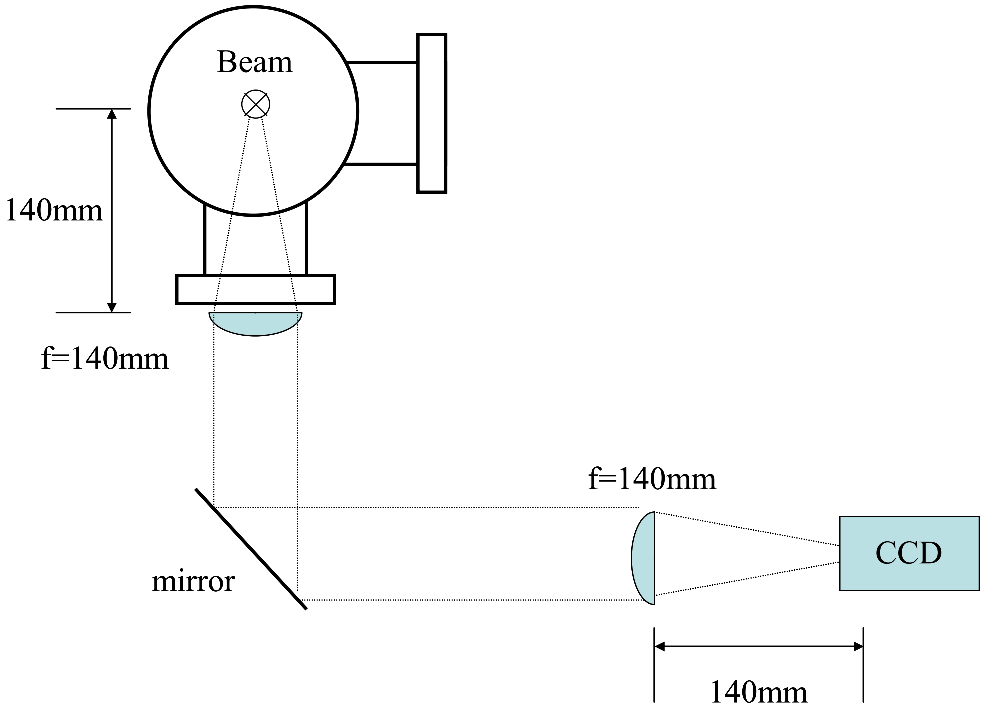
- When three degrees of freedom are independent of each other ($\psi_c = 0$), nothing takes place in *x* and *y* directions even if we strongly cool the *z* direction.
- Switch on the coupling potential to correlate the harmonic motions in the three directions. Linear coupling potentials should be employed for this purpose:

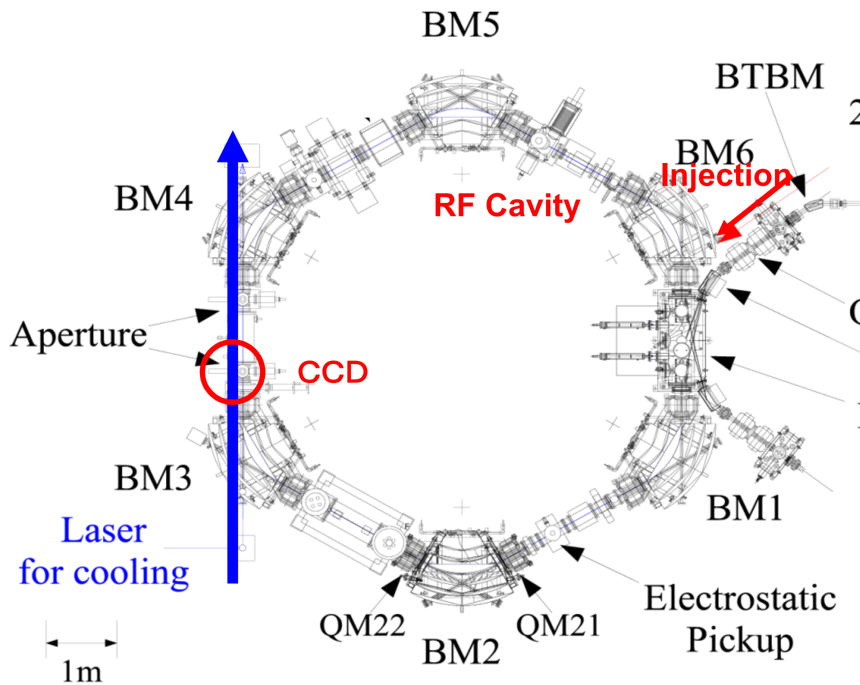
$$\psi_c = g_1 xy \cdot \delta_p(s - s_1) + g_2 xz \cdot \delta_p(s - s_2)$$

- Move the operating point onto coupling resonance:

$$\nu_x - \nu_y = \text{integer}, \quad \nu_x - \nu_z = \text{integer}$$

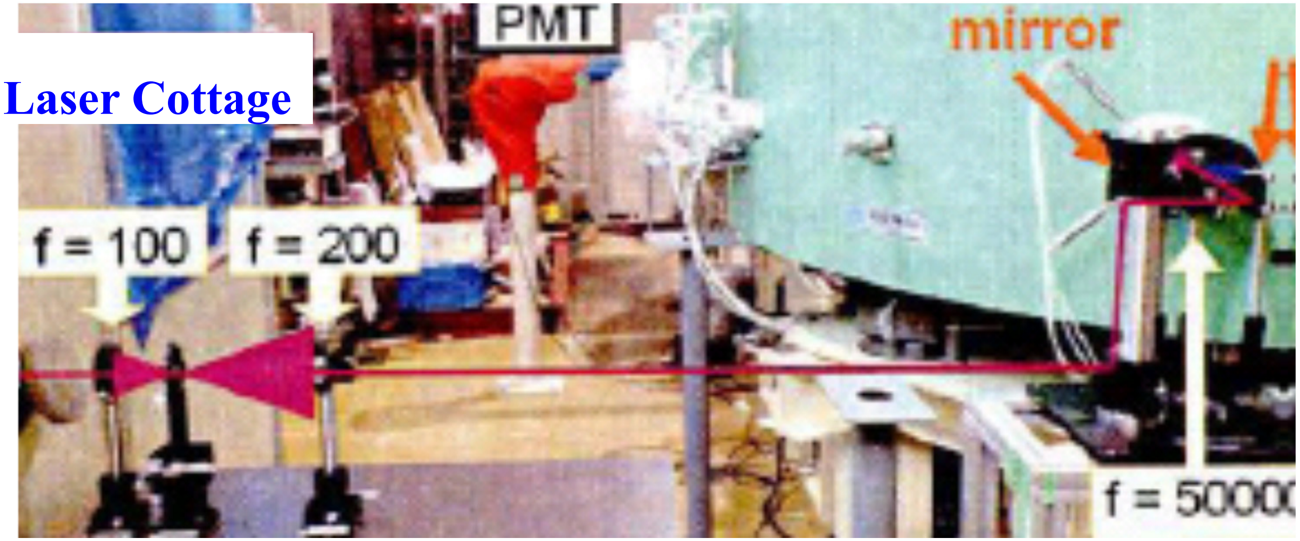
Observation of Transverse Beam Size by CCD Camera

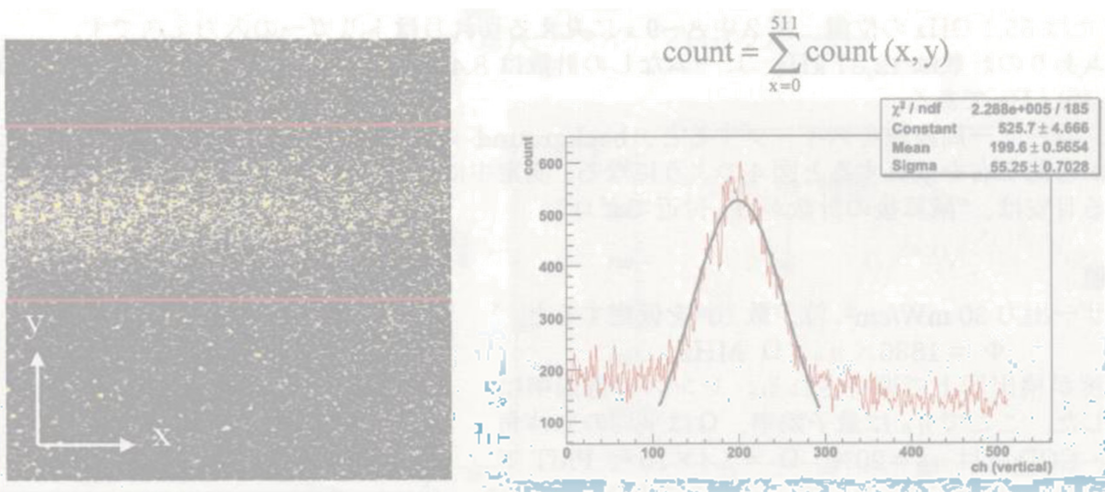


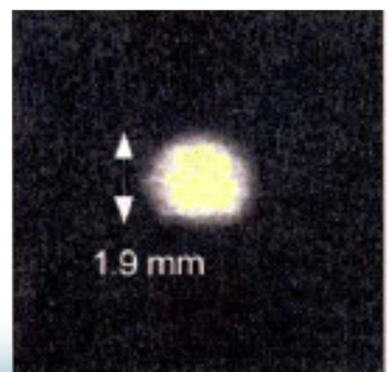


Cooled CCD Camera
(Hamamatsu Photonics C7190-11W)

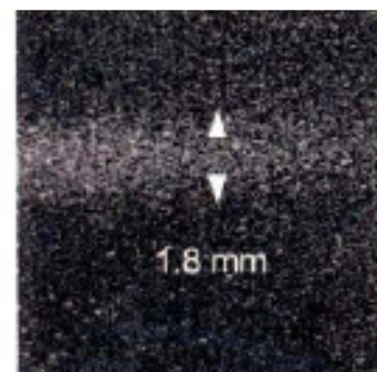
Ion Observation with Emitted Light







Laser Profile



Fluorescent light from the ion beam

L-H Coupling

Only the relation:

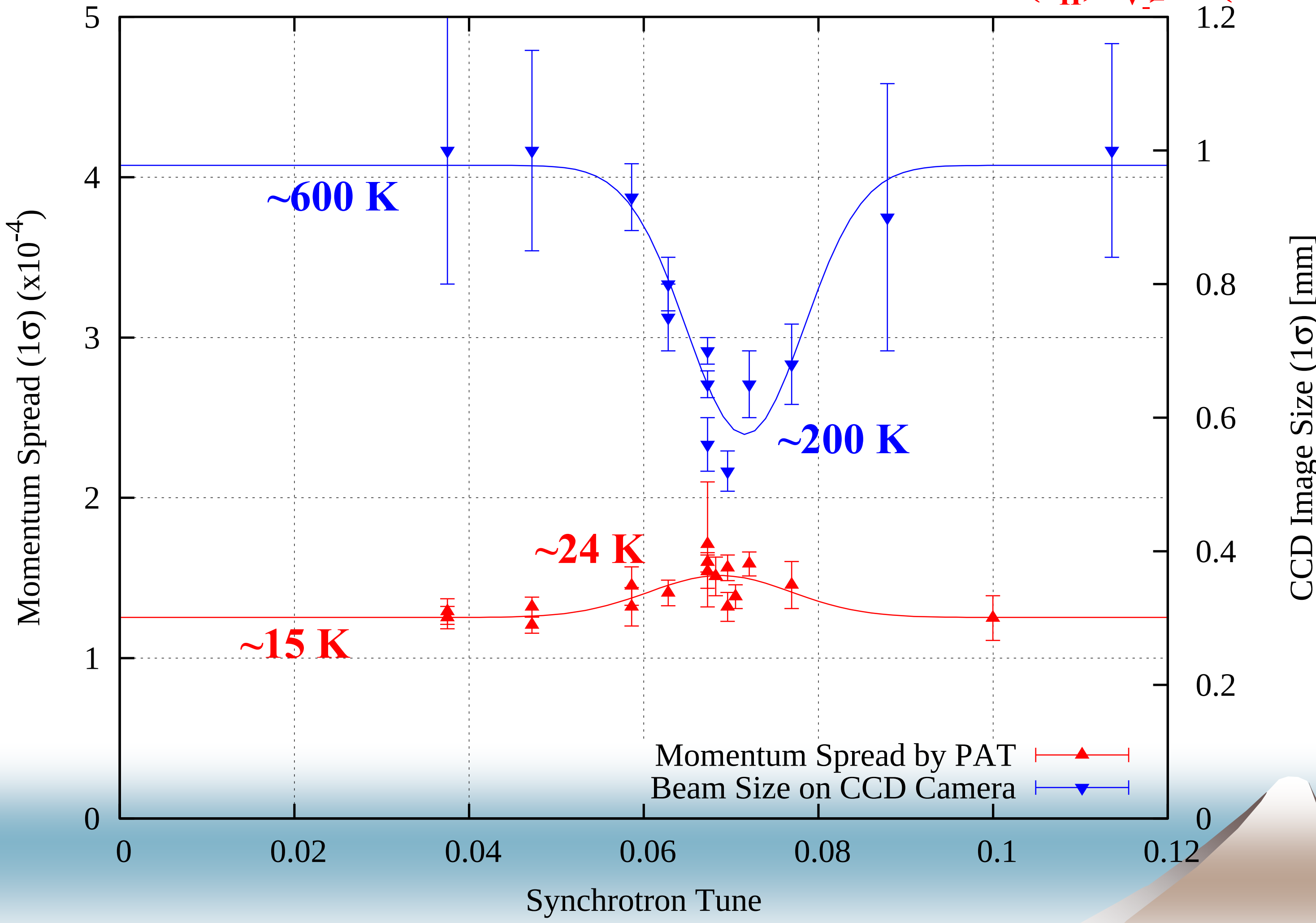
$\nu_H - \nu_s = \text{integer}$

is satisfied!

M. Nakao et al. Phys. Rev. ST Accel. Beams 15, 110102 (2012)

Transverse Laser Cooling by Synchro-Betatron Coupling

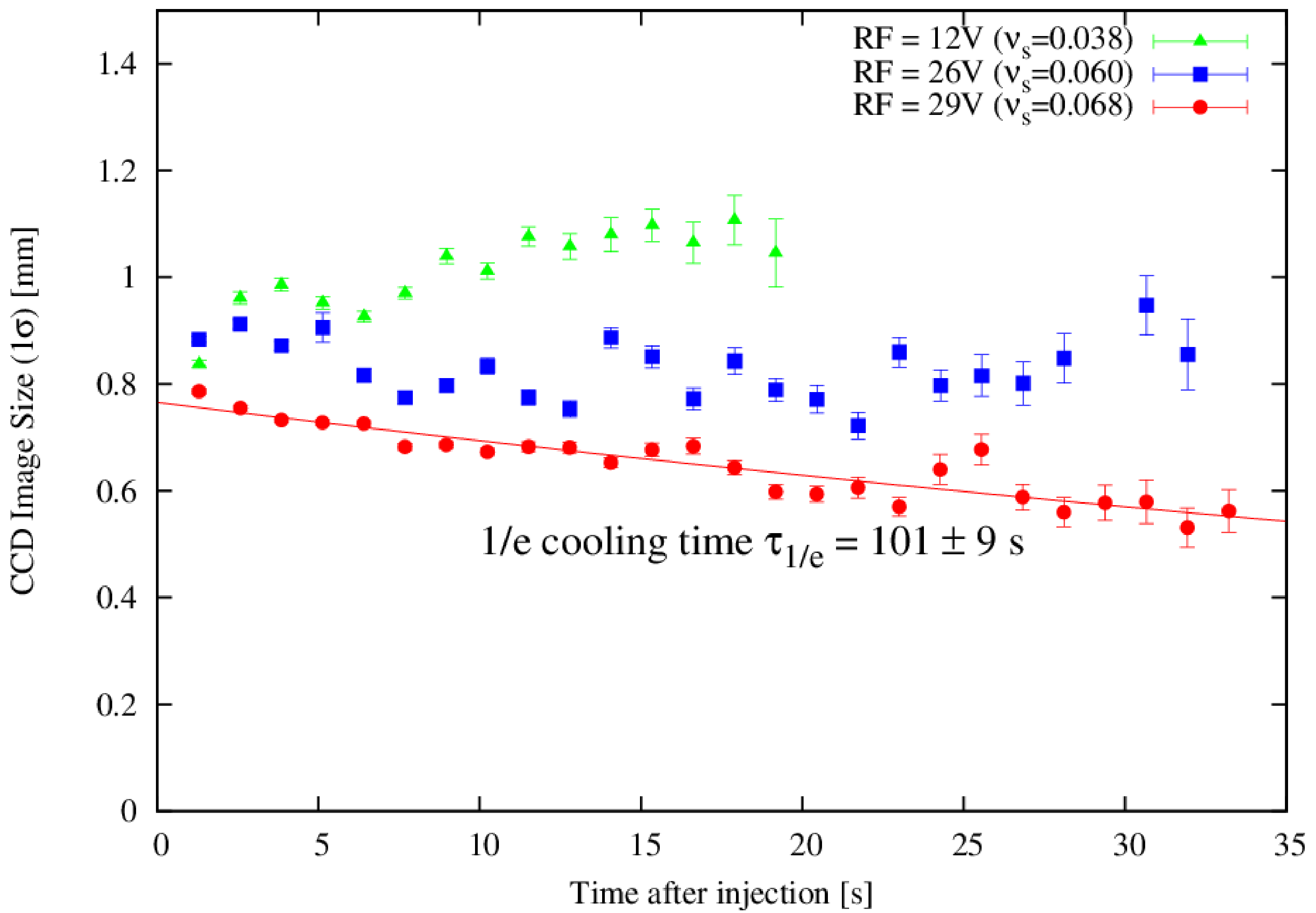
$(\nu_H, \nu_V) = (2.068, 1.105)$



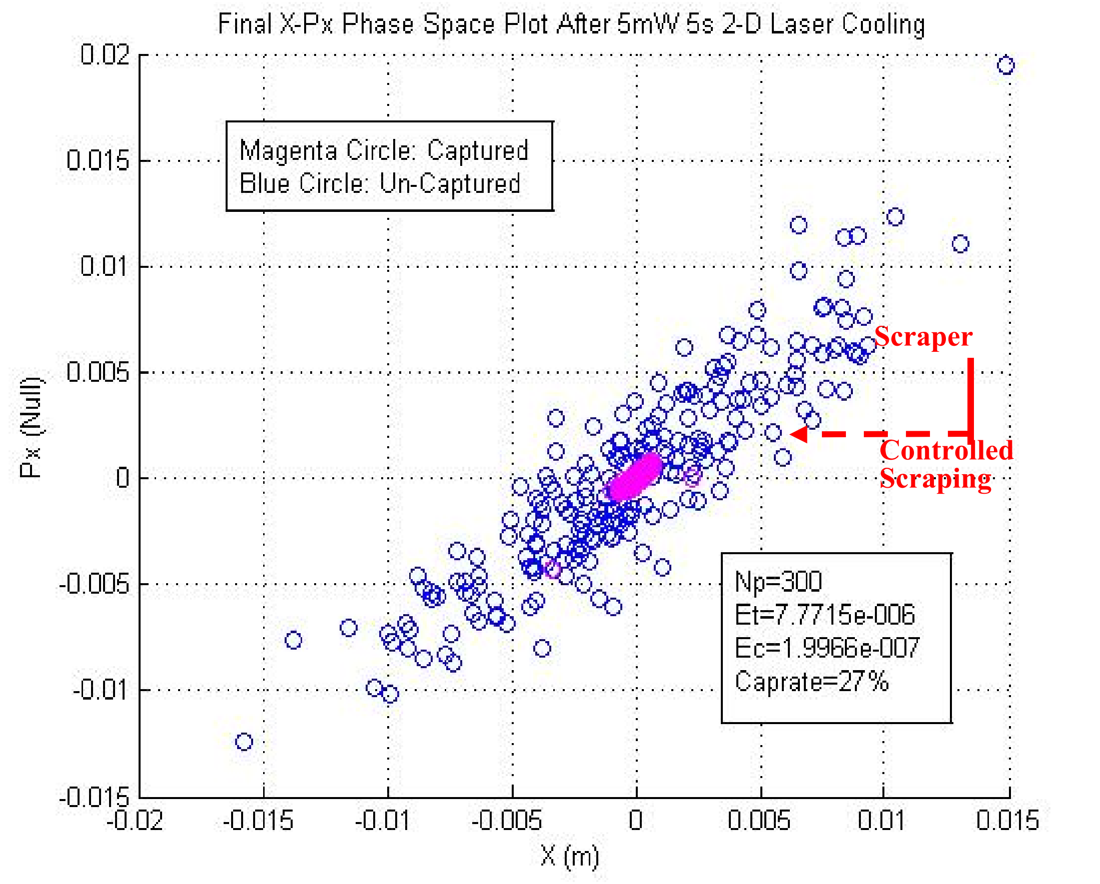
Time Variation of Transverse Beam Size for Various Synchrotron Tune

(Beam Intensity 1 x 10^7)

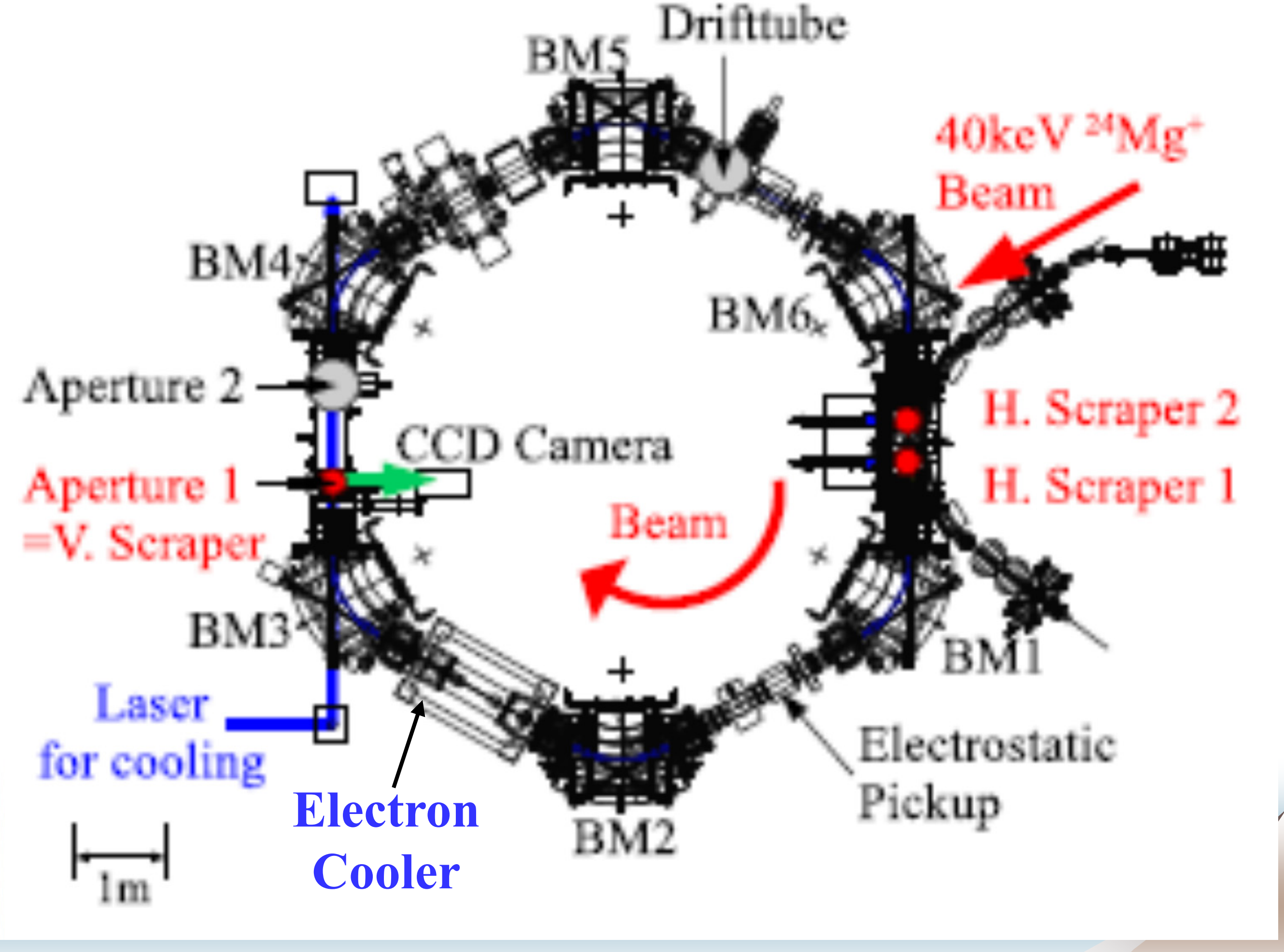
$(\nu_H, \nu_V) = (2.068, 1.105)$



Controlled Scraping to Suppress IBS Effects

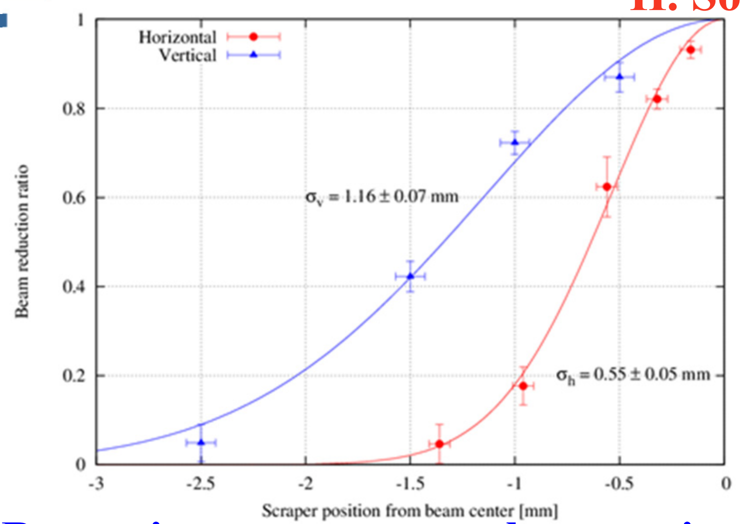


Scraping System for Intensity Reduction and Beam Size Measurement

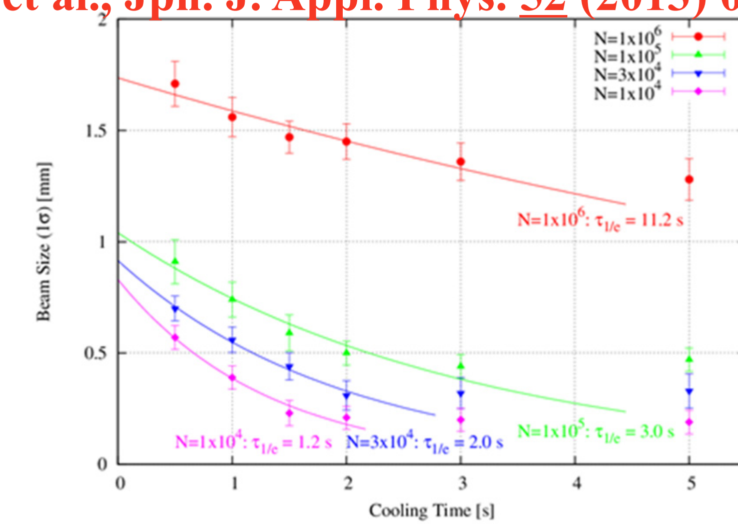


Efficiency Increase of Transverse Laser Cooling by SBRC

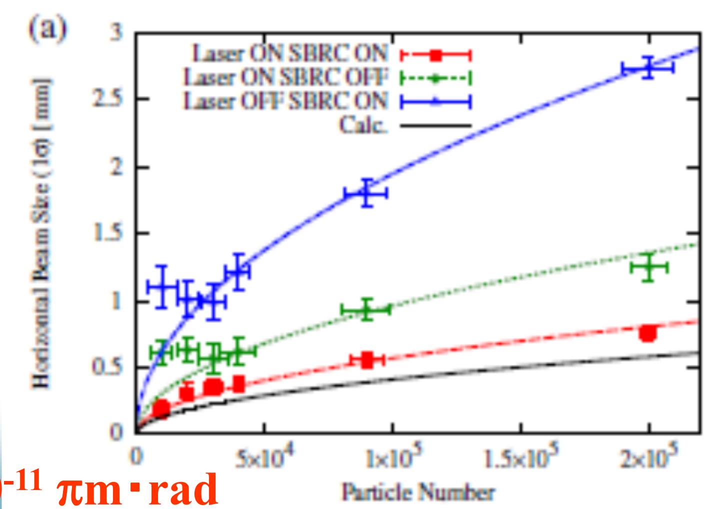
H. Souda et al., Jpn. J. Appl. Phys. 52 (2013) 030202



Beam size measurement by scraping



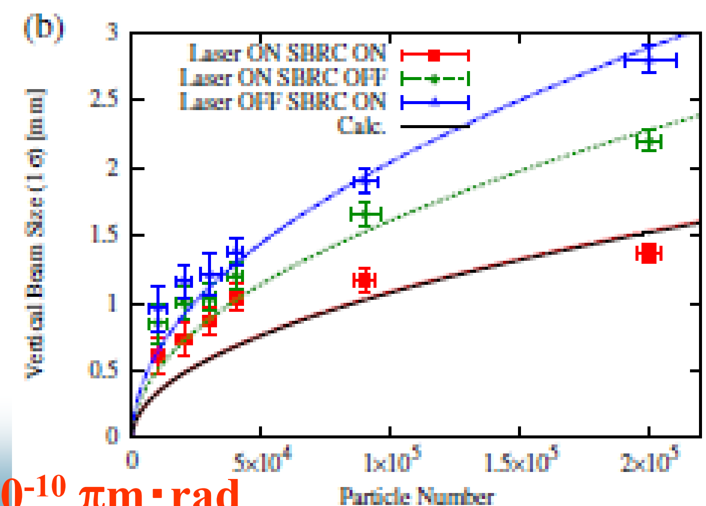
Time dependence of the cooled beam size



20 K

7.0×10^{-11} πm・rad

Horizontal beam size



29 K

1.9×10^{-10} πm・rad

Vertical beam size

Ion Number Dependence of the Indirectly Laser cooled Beam Size

H-V Coupling is added

Relations:

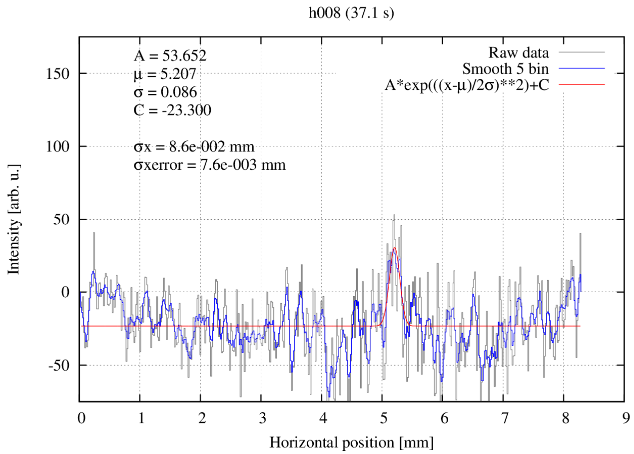
$$\nu_H - \nu_s = \text{integer},$$

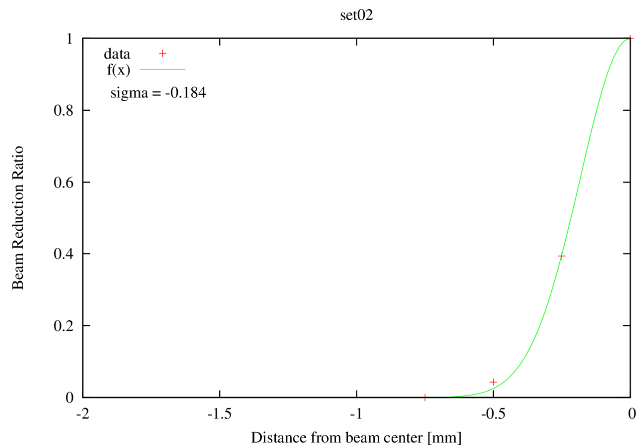
$$\nu_H - \nu_V = \text{integer}$$

are satisfied together with the use of a Solenoid

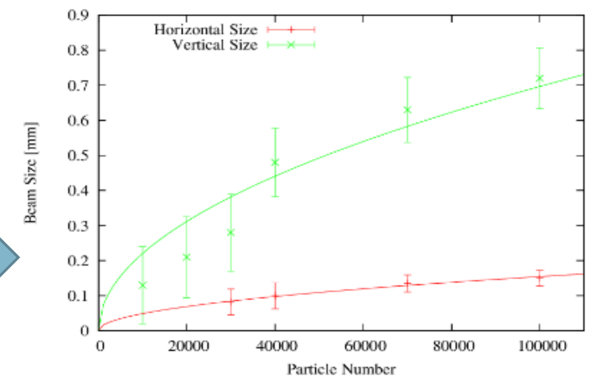
3 D Laser Cooling + INDAC

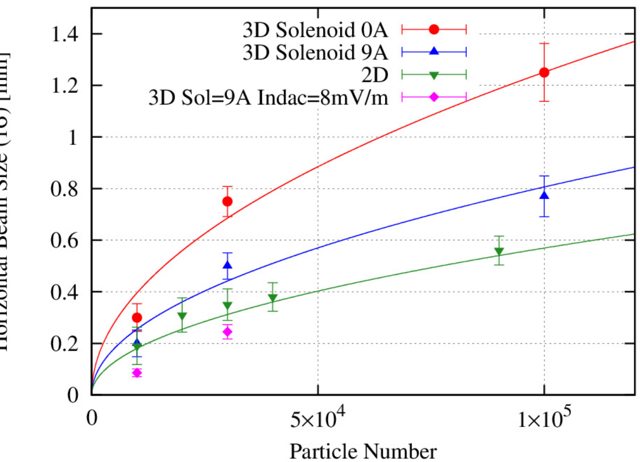
Operation Point = (2.068, 1.07)

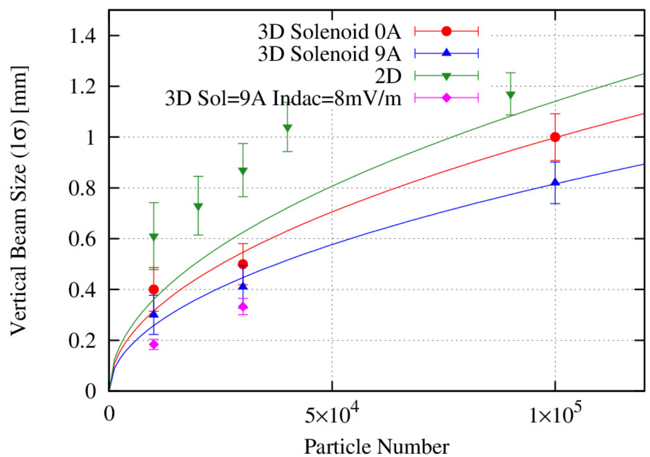




Optimization







Horizontal

6.4 K

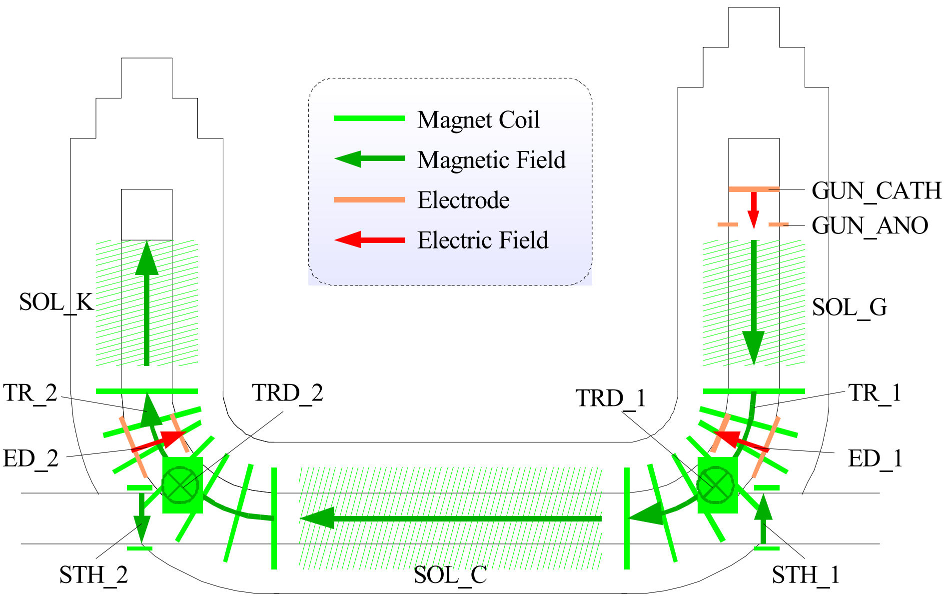
1.3×10^{-11} πm・rad

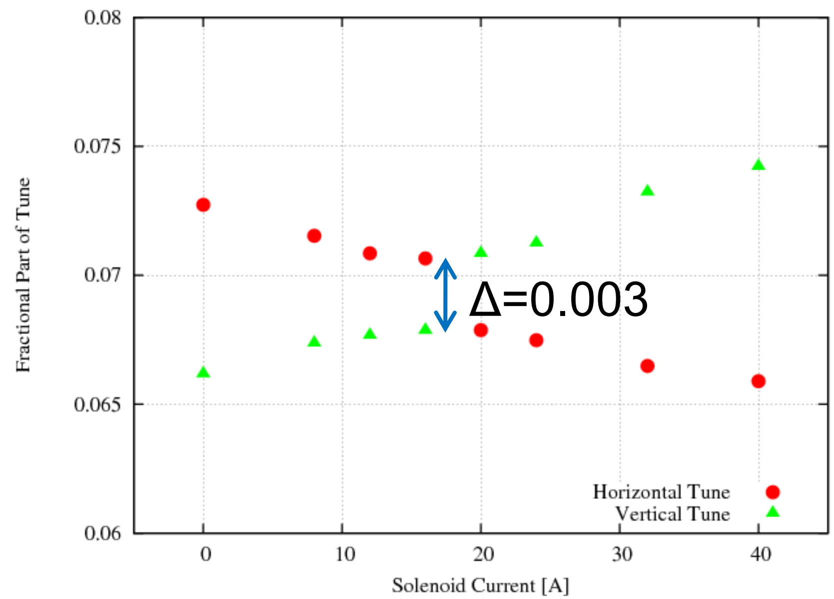
Vertical

2.1 K

8.5×10^{-12} πm・rad

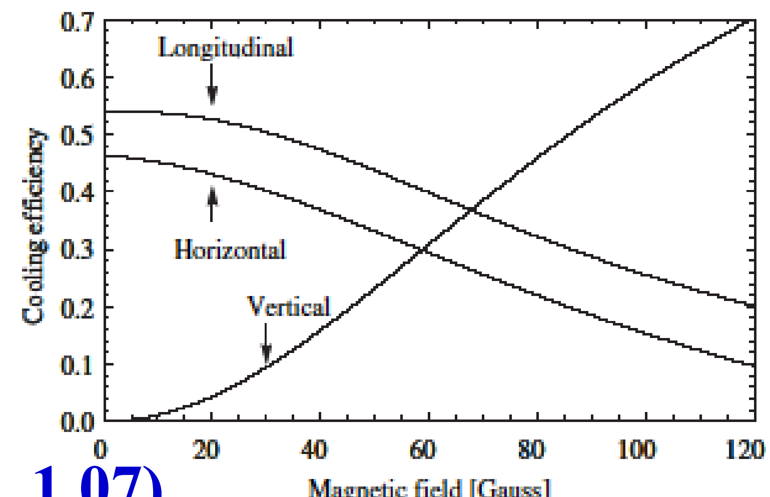
H-V Coupling with a Solenoid Field





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

Operating Point ~ (2.073, 1.067)

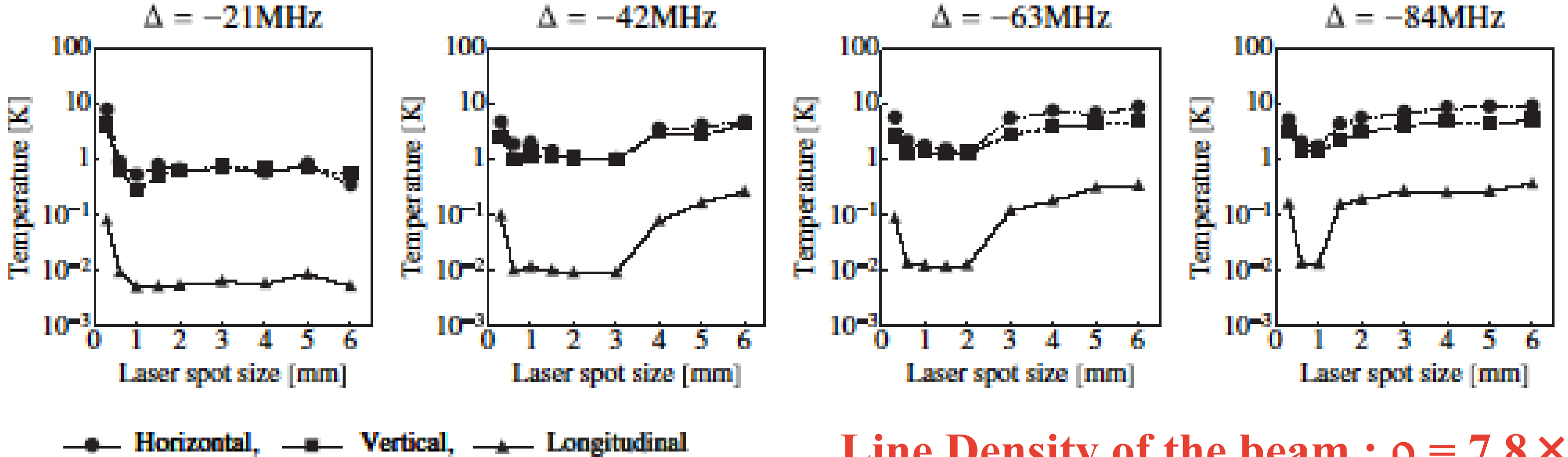


Operating Point ~ (2.07, 1.07)

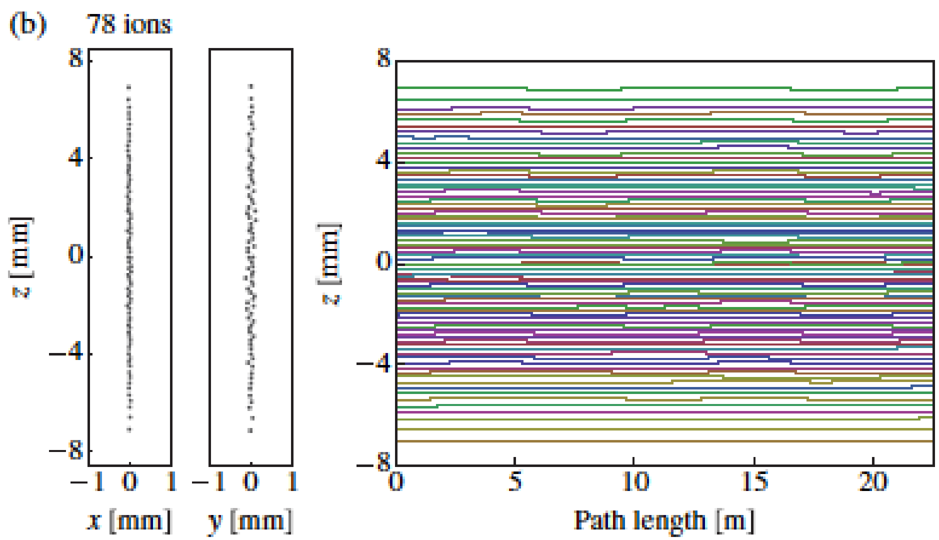
K. Osaki and H. Okamoto, Prog. Theor. Exp. Phys., 053G01, (2014)

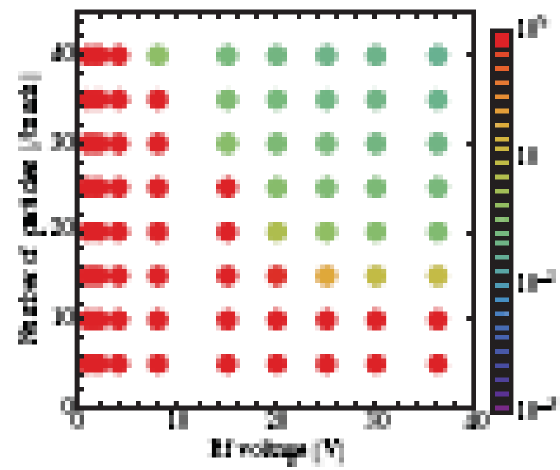
Prediction of 1D Longitudinal String (Bunched)

Laser spot size : 1.5 mm, detuning -42MHz, with RF Voltage Ramping



Line Density of the beam : $\rho = 7.8 \times 10^3$ 1/m

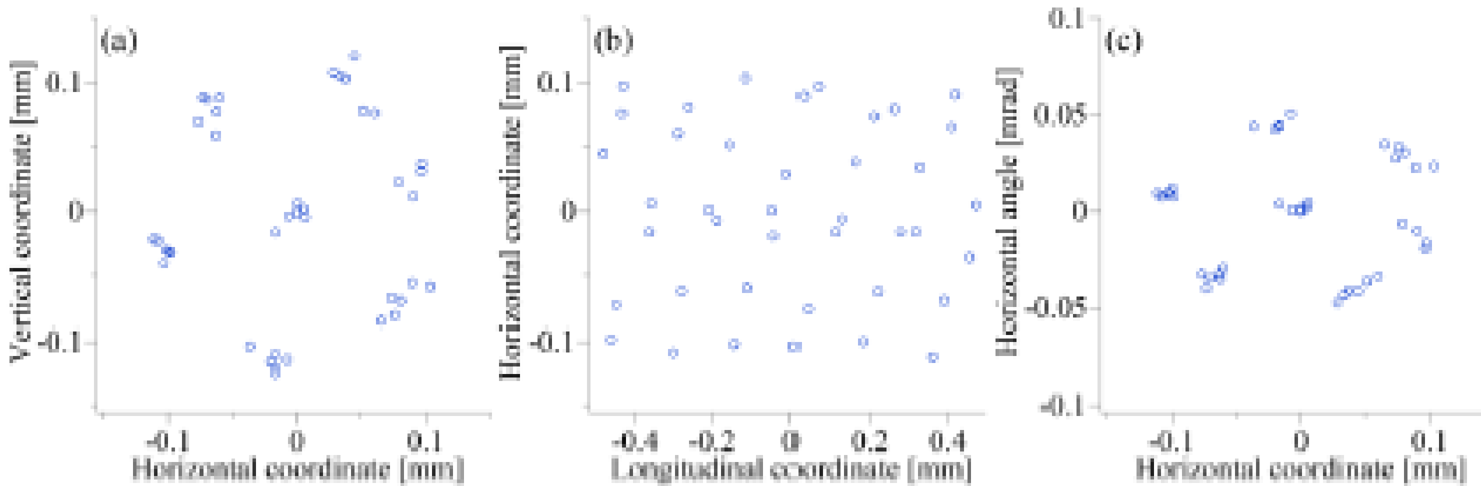


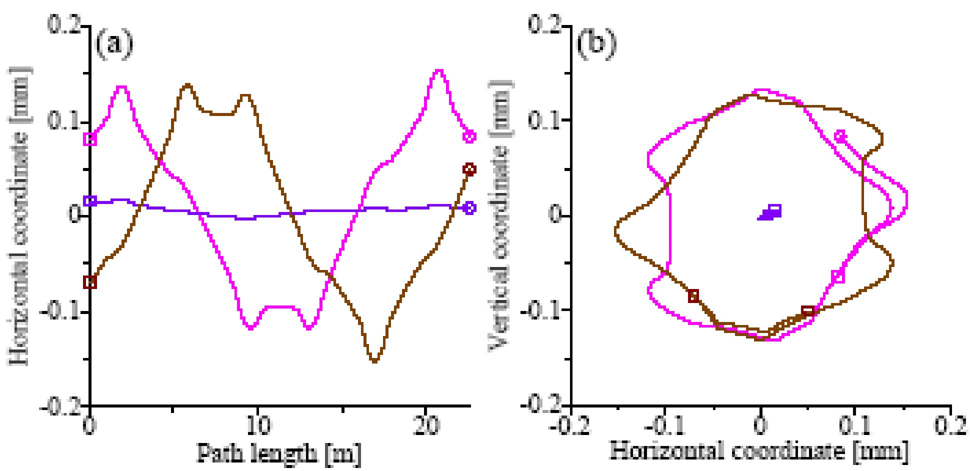


Longitudinal 0.001 K: 10^{-13} πm･rad, Transverse 0.1 K: 10^{-12} πm･rad

Y. Yuri, JPS. Conf. Proc. **1**, 013014 (2014)

MD Simulation of 3D Ordered State



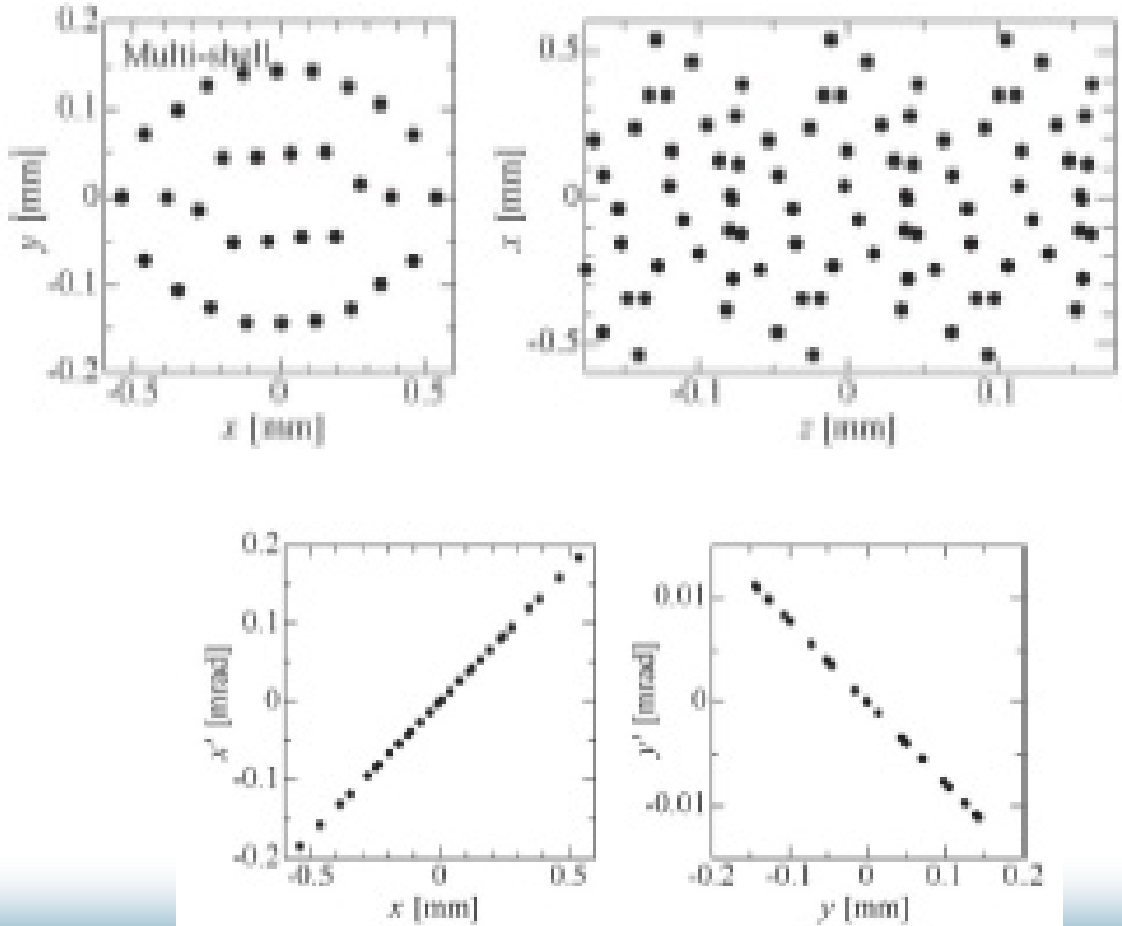


Operation Point = (1.44, 1.44)
Laser Waist Size ~2.5 mm (1σ)
3 mm shifted in parallel to $^{24}Mg^{+}$ beam
Ramped final laser detuning ~-61 MHz

Line Density of the beam : $\rho = 4 \times 10^4$ 1/m

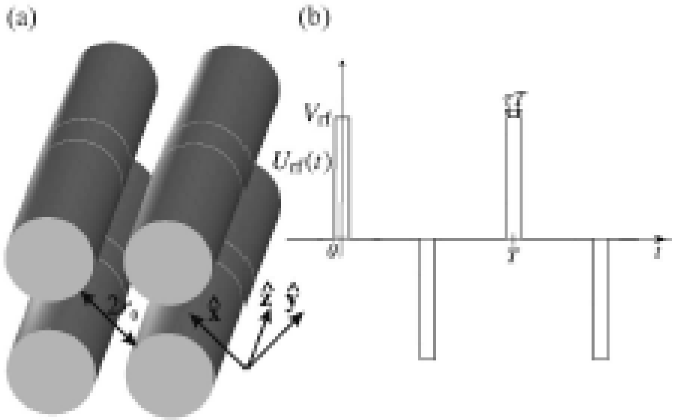
Predicted Temperature
= 6mK (longitudinal)
= 0.6K (Transverse)

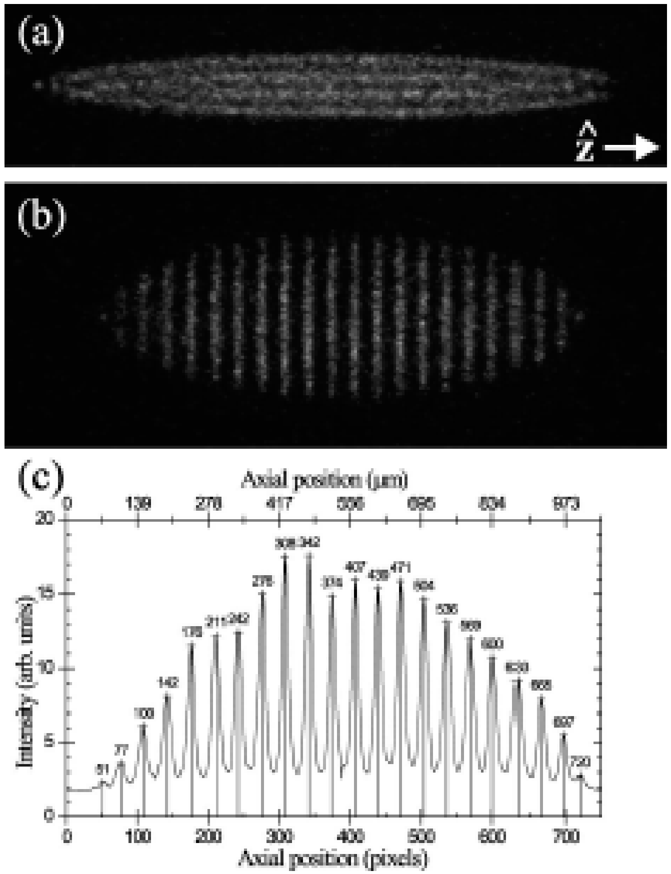
Double-Shell Crystalline Beam



N. Kjærgaard and M. Drewsen, Phys. Rev. Lett., **91**, 095002 (2003)

"String of Discs" observed at Linear Paul Trap





$$\Psi(x,y,z,t) = \frac{U_{rf}(t)}{2r_0^2}(x^2 - y^2) + \frac{U_{dc}\eta}{2z_0^2}[2z^2 - (x^2 + y^2)],$$

Comparison of Experimental Data and MD Simulations

Table 2 Comparison of laser cooled ion beam temperatures. (Shaded columns represent the recent MD simulations.)

Year Ring	Method	Ion	Kinetic Energy	Intensity	Beam Density	$T_{//}$ (K)	T_H (K)	T_V (K)	Ref.
1996 TSR	IBS	$^{9}Be^{+}$	7.3 MeV	2.0×10^{7}	3.6×10^{5}	15	4000	500	[15]
1998 TSR	Dispersive cooling	$^{9}Be^{+}$	7.3 MeV	1.0×10^{7}	1.8×10^{5}	few tens	~500#	~150 #	[16]
1999 ASTRID	IBS	$^{24}Mg^{+}$	100 keV	7×10^{6}	1.8×10^{5}	2-5	17	21	[17]
2001 PALLAS	RFQ	$^{24}Mg^{+}$	1 eV	1.8×10^{4}	5.0×10^{4}	<0.003	$T_{\perp}$<0.4		[28]
2008 S-LSR	IBS	$^{24}Mg^{+}$	40 keV	1.0×10^{7}	4.4×10^{5}	11	-	500	[22]
2009 S-LSR	W SBRC (2D)	$^{24}Mg^{+}$	40 keV	1.0×10^{7}	4.4×10^{5}	27	220$		[25]
2009 S-LSR	WO SBRC	$^{24}Mg^{+}$	40 keV	1.0×10^{7}	4.4×10^{5}	16			[25]
2012 S-LSR	W SBRC (2D)	$^{24}Mg^{+}$	40 keV	1×10^{4}	4.4×10^{2}	(0.4)	20	29	[26]
2013.2.1 S-LSR	W SBRC (3D)	$^{24}Mg^{+}$	40 keV	1×10^{4}	4.4×10^{2}	-	40	11	[27]
2013.3.7 S-LSR (Δf=-190 MHz)	W SBRC (3D) (INDAC ON)	$^{24}Mg^{+}$	40 keV	1×10^{4}	4.4×10^{2}	-	8.1	4.1	[27]
2013.3.22 S-LSR (Δf=-26 MHz)	W SBRC (3D) (INDAC ON)	$^{24}Mg^{+}$	40 keV	1×10^{4}	4.4×10^{2}	-	6.4 (3×10^{4})	2.1	[27]
Simulation with MD (Δf=-42MHz)	W.SBRC (3D) (RF ramping)	$^{24}Mg^{+}$	40 keV	7.8×10^{3}	6×10^{3}	~0.001	~0.1	~0.1	[30]
Simulation with MD (Δf=-61MHz)	W.SBRC (3D) (W Dispersive cooling)	$^{24}Mg^{+}$	40 keV	9×10^{3}	4.0×10^{4}	0.003	0.6	0.6	[31]

Conclusions

1. Lowest temperature (smallest normalized emittance) was realized for moving ion beam of non-negligible speed by Doppler Laser Cooling with SBRC.
2. Its normalized temperature comes close to the one of 1D Longitudinal String predicted by MD simulation although the momentum spread has not yet measured for such a small beam intensity.→Urgent Technical Issue (Improvement of Observation Sensitivity is needed!!)
3. 3D Ordered State is also predicted by Dispersive Cooling of Coasting Beam following the one at an Ion Trap.

=>These prediction is desired to be realized experimentally as soon as possible!!

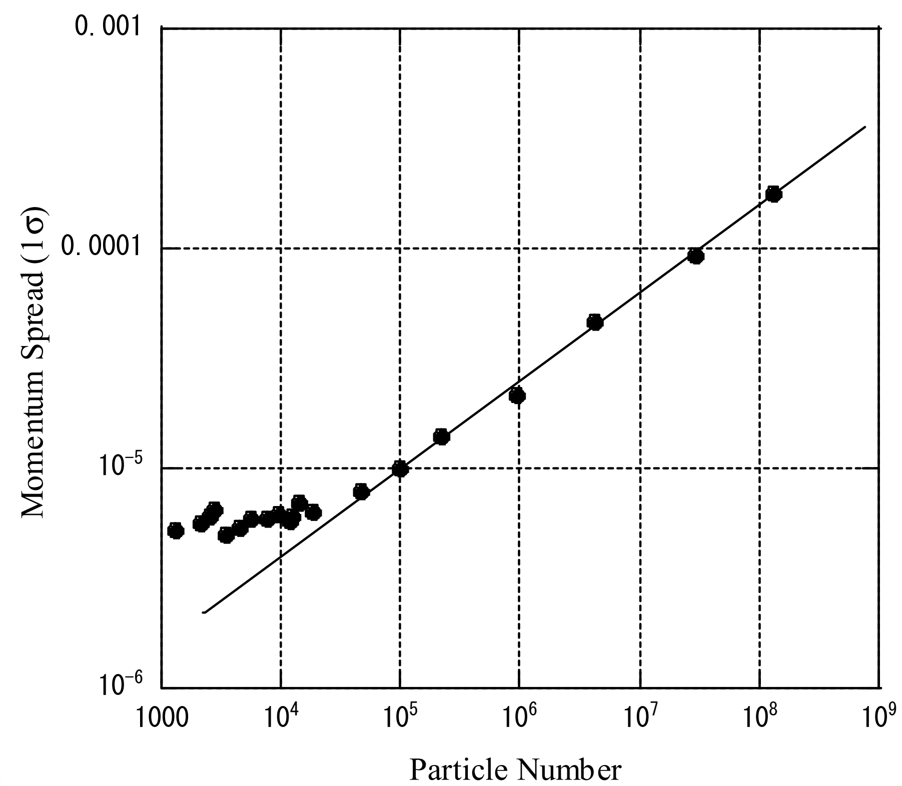
Thank you for your attention!!

Vielen Dank für Ihre Aufmerksamkeit!!

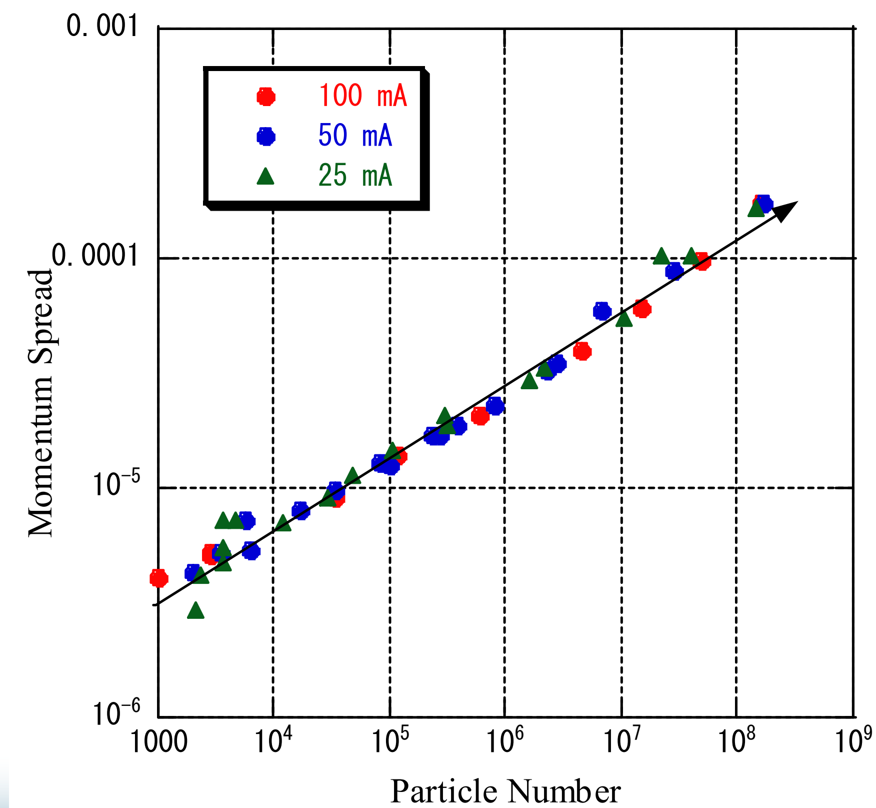
Borrowed from Dr. M. Grieser

Back Up Slides

Fractional Momentum Spread vs Particle Number



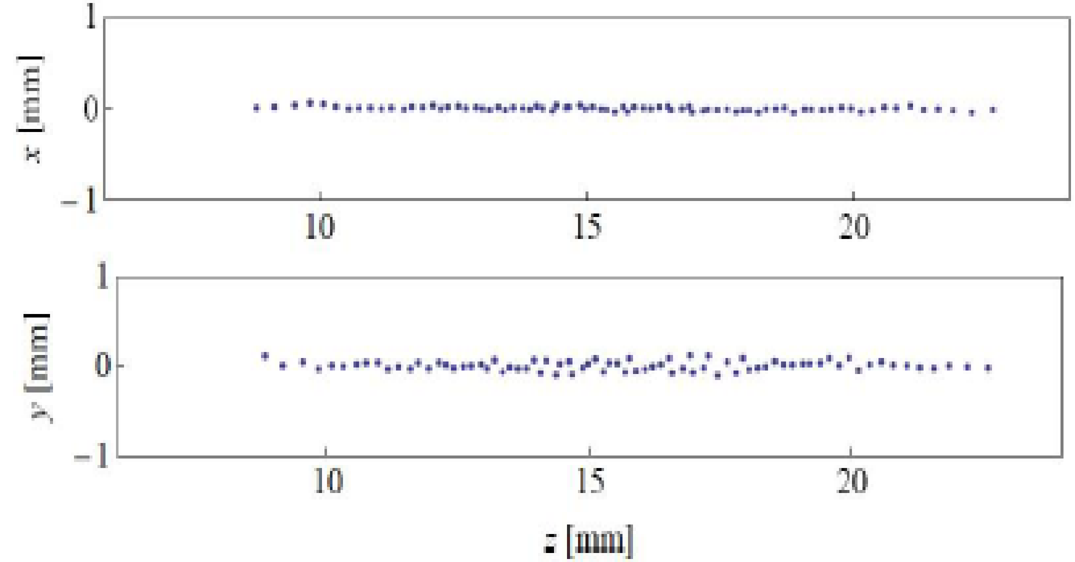
Data in Feb., 2006



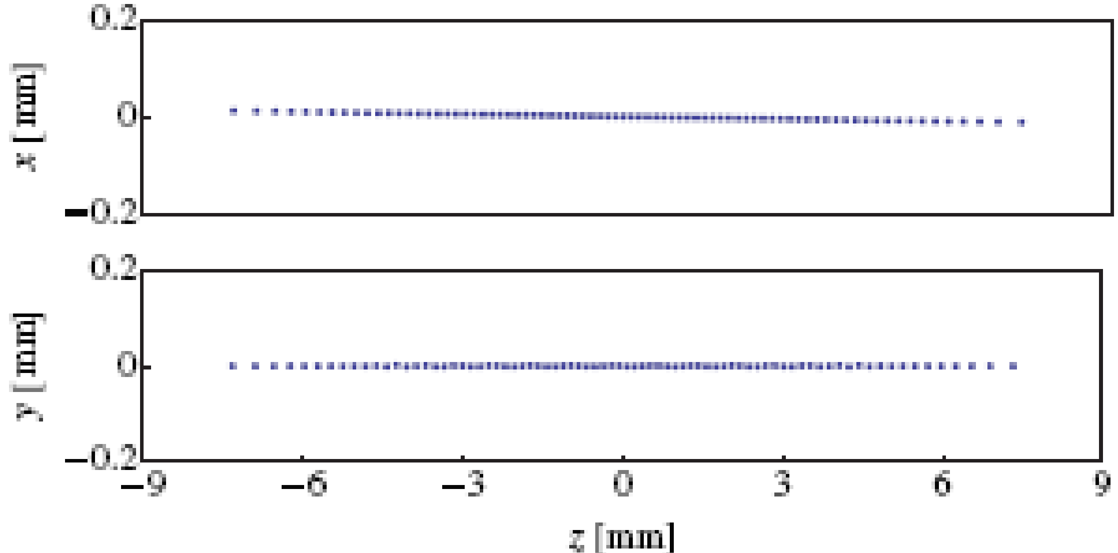
Data on the 8th, June, 2006

Comparison of 1 D Longitudinal String Structure

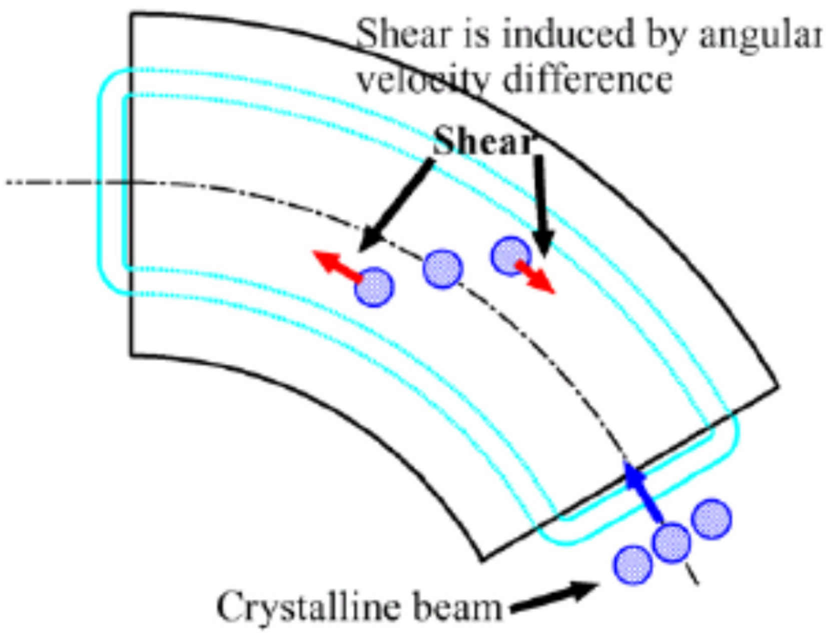
Assume real Laser used at S-LSR Experiment

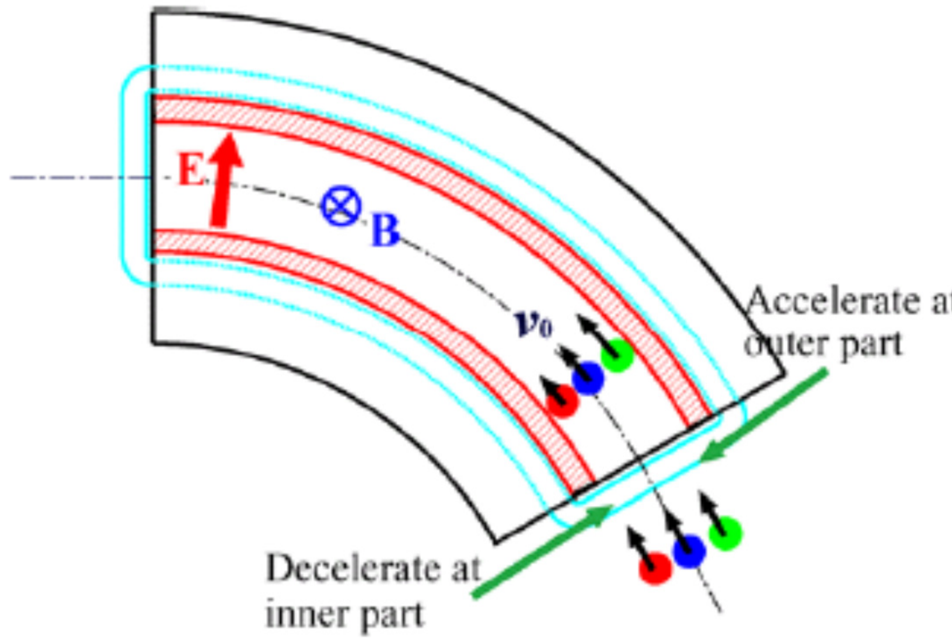


Linear dissipative force in 3 dimensions are assumed



Shear Heating and Dispersion Suppressor





This idea was first proposed by W. Henning: Anns. Phys. Lpz. 19, 335 (1934) and W.E. Millet :Phys. Rev. 74, 1058 (1948) and is also recently claimed by R.E. Pollock, Z. Phys. :A. Hadrons and Nuclei. 341, 95 (1991)

Dispersion Suppressor

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

Electric Field

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

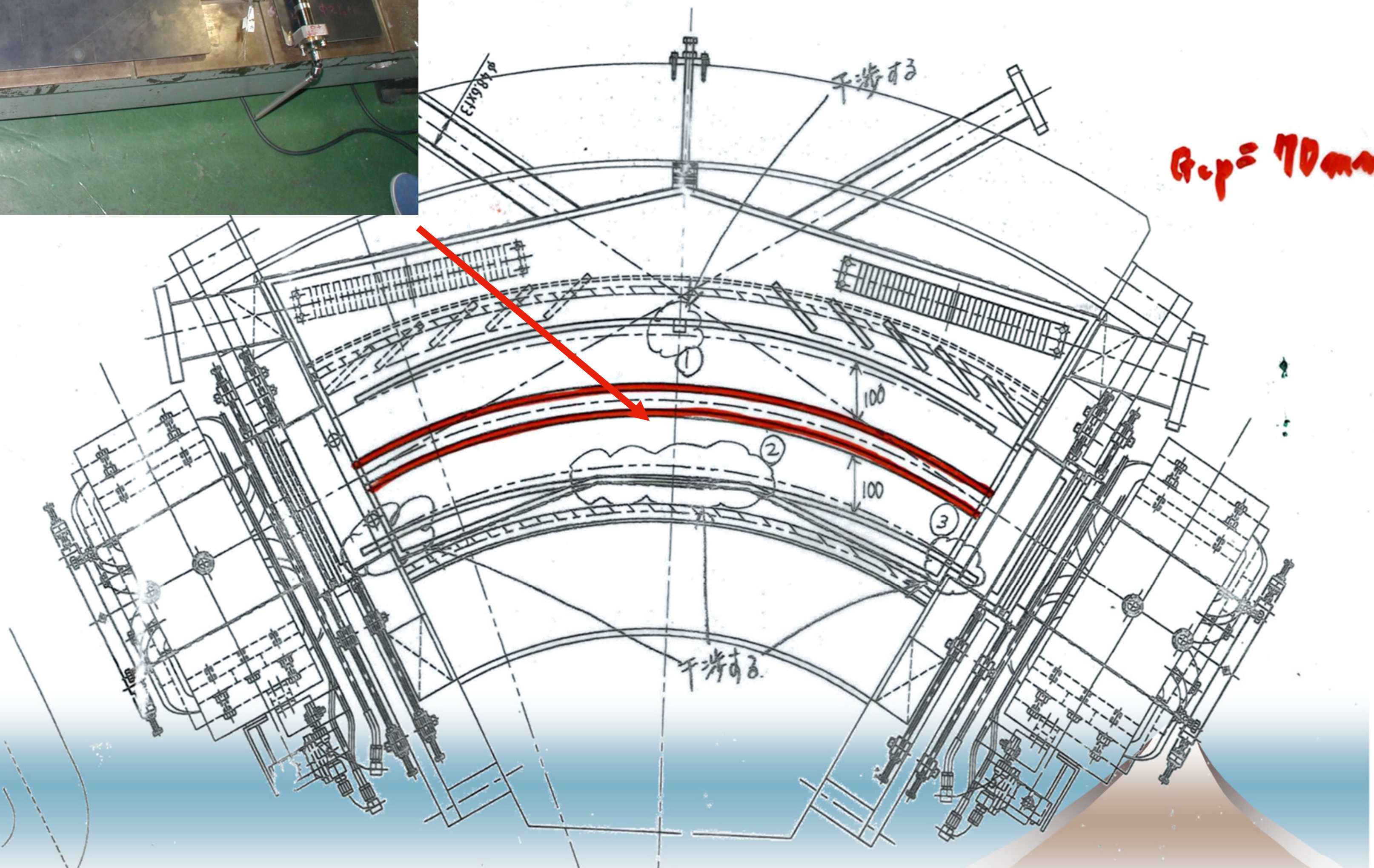
Magnetic Field

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

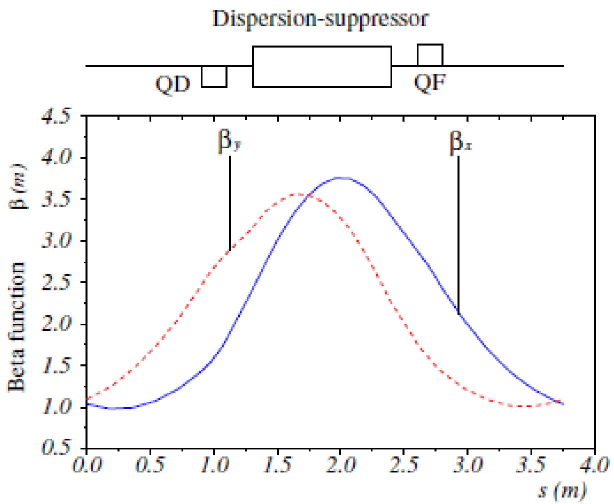
Non-relativistic Case

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

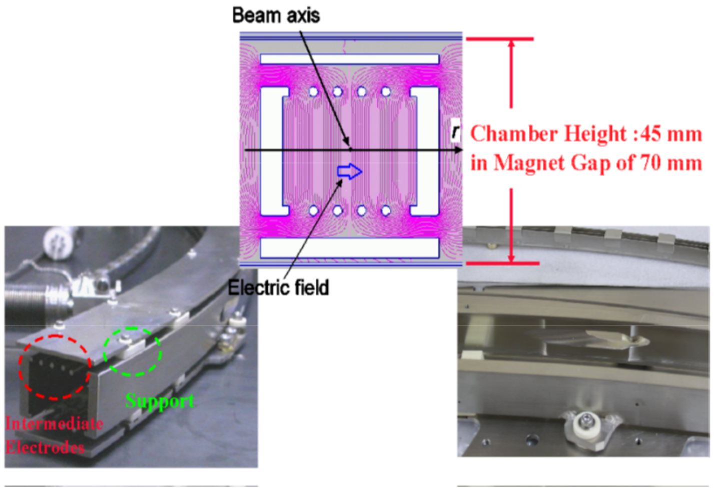
Vacuum Chamber in the Magnet Section (includes the Electrodes)



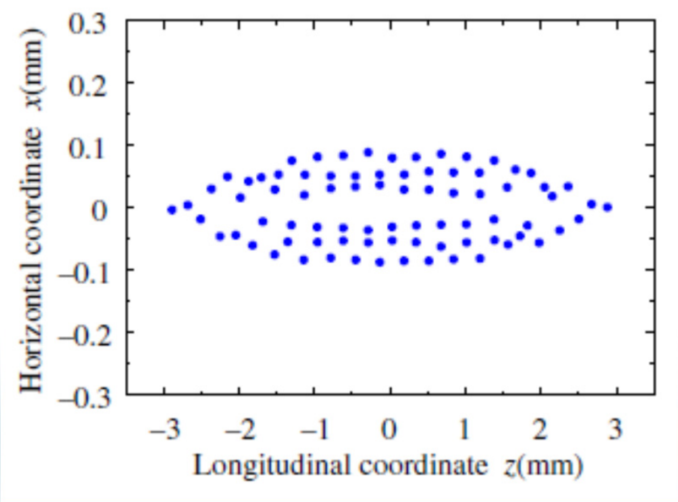
3D Laser Cooling with Dispersion Free Lattice



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



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

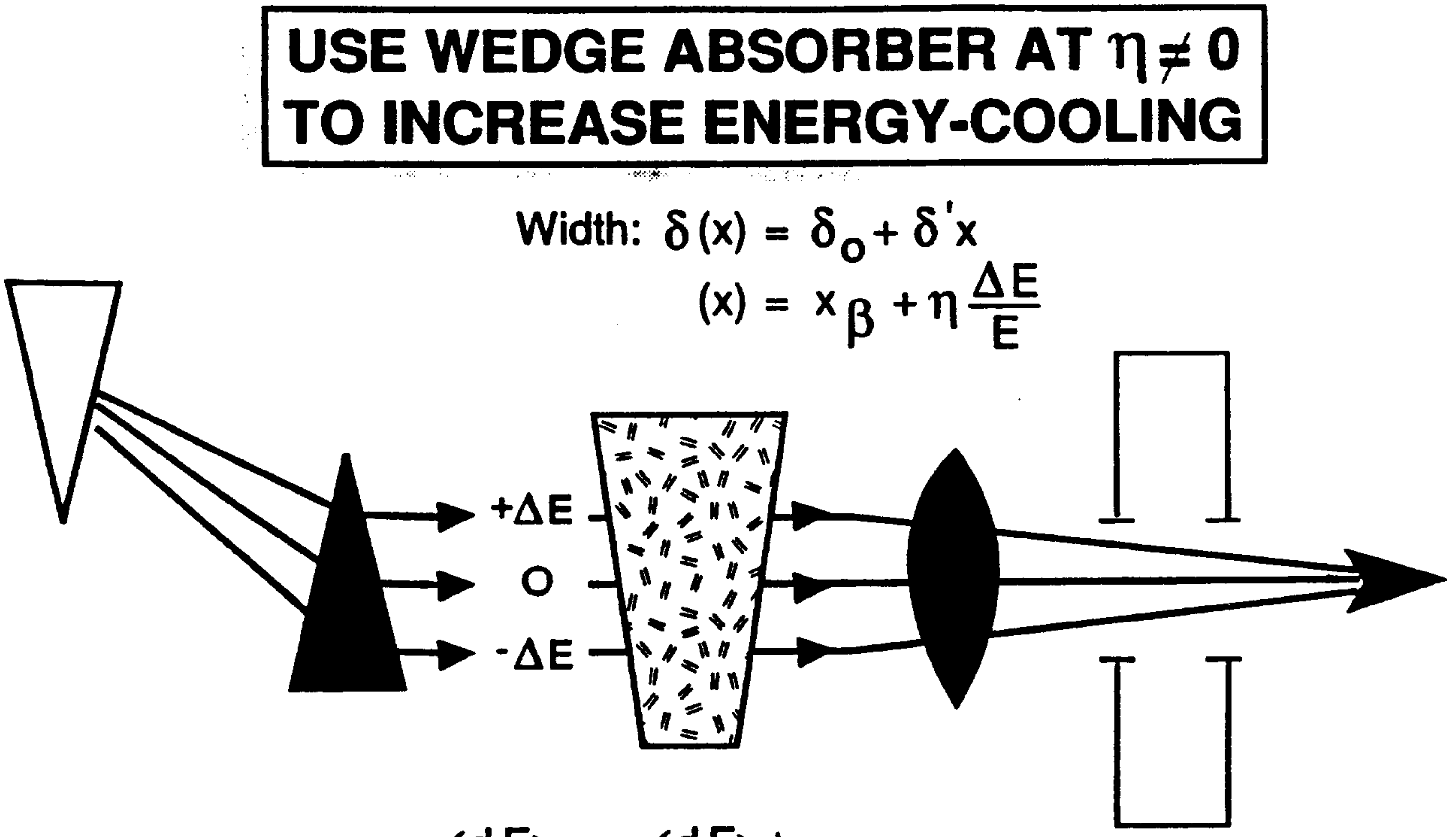


A coupling cavity is needed

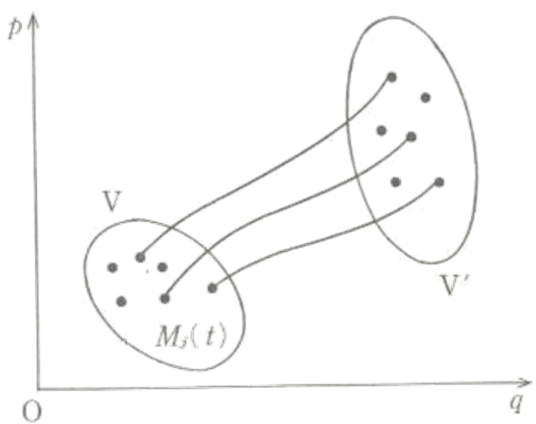
To couple the longitudinal and transverse degrees of Freedom.

A few layers 3D crystalline beam is expected.

Ionization Cooling



Liouville's Theorem



Trajectories in the 6 dimensional phase space does not cross

Laminar Flow-velocity distribution at a point is single valued.

Phase Space Density f (x,p) does not change

$$\frac{df}{dt} = 0$$

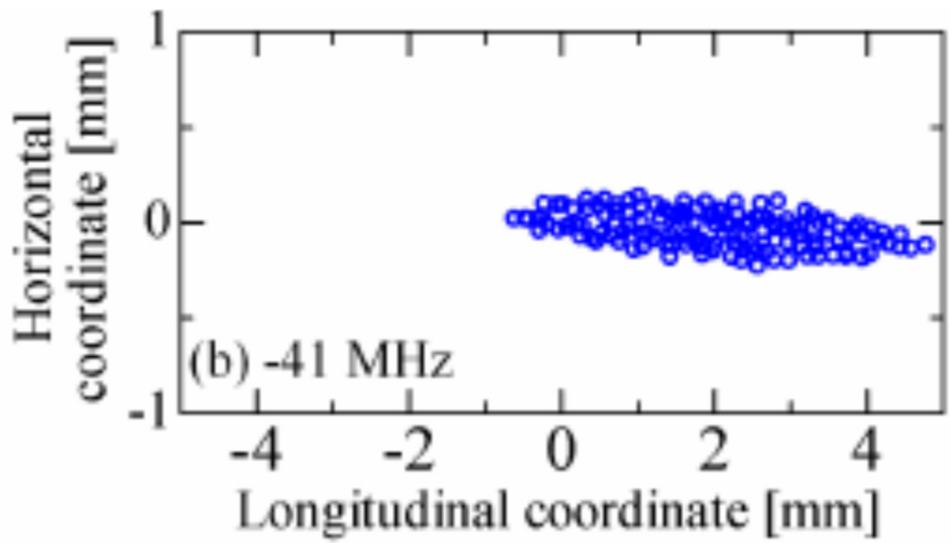
Phase Space Volume occupied by the beam does not change

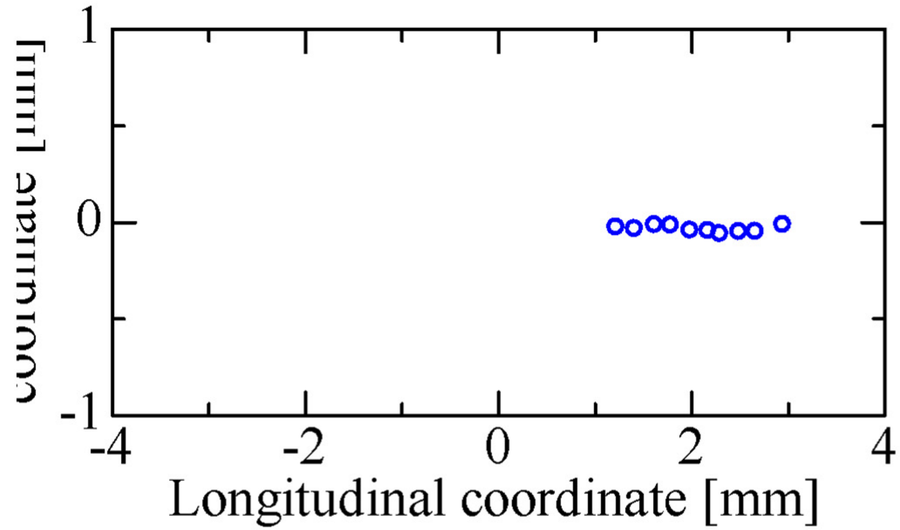
In case, inter-particle interaction exists, phase space volume increases→Entropy Increases (2-nd law of Thermodynamics)

Beams in the accelerators basically follows Liouville's Theorem (without inter-particle interaction)

By Y. Yuri et al. Proc. of COOL'13

MD Simulation





N = 10^4, detuning is -41 MHz
Laser Power is 8 mW

Experimentally attained!!
T_H= 6.4 K, T_V = 2.1 K

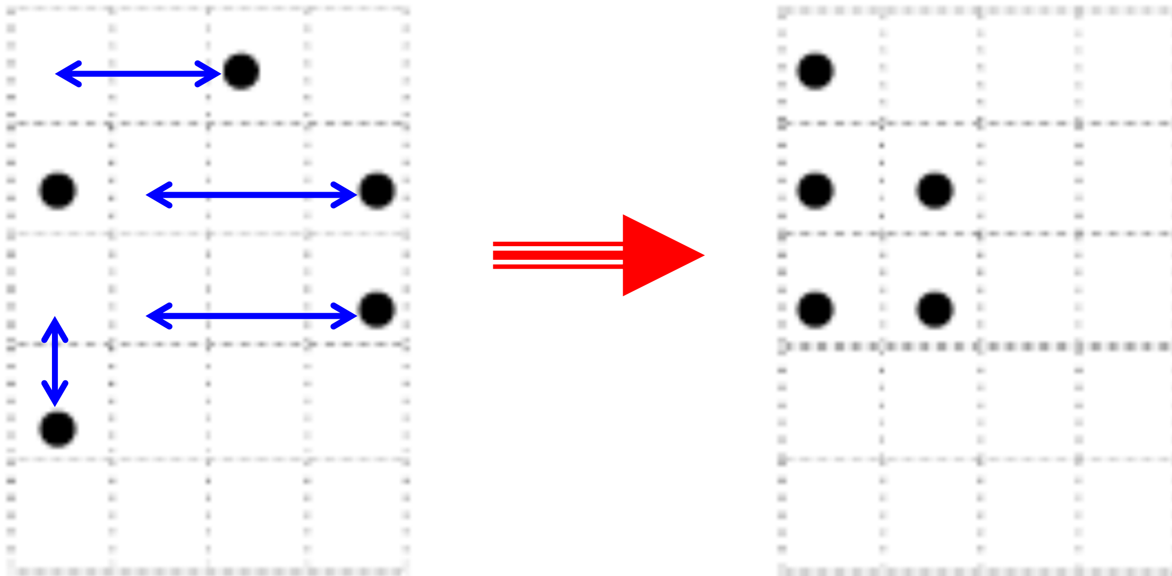
N = 10^3, detuning is -41 MHz
Laser Power is 8 mW

↓

1 D Crystalline stringの形成

Stochastic Cooling

Principle of Stochastic Cooling
by Simon van der Meer

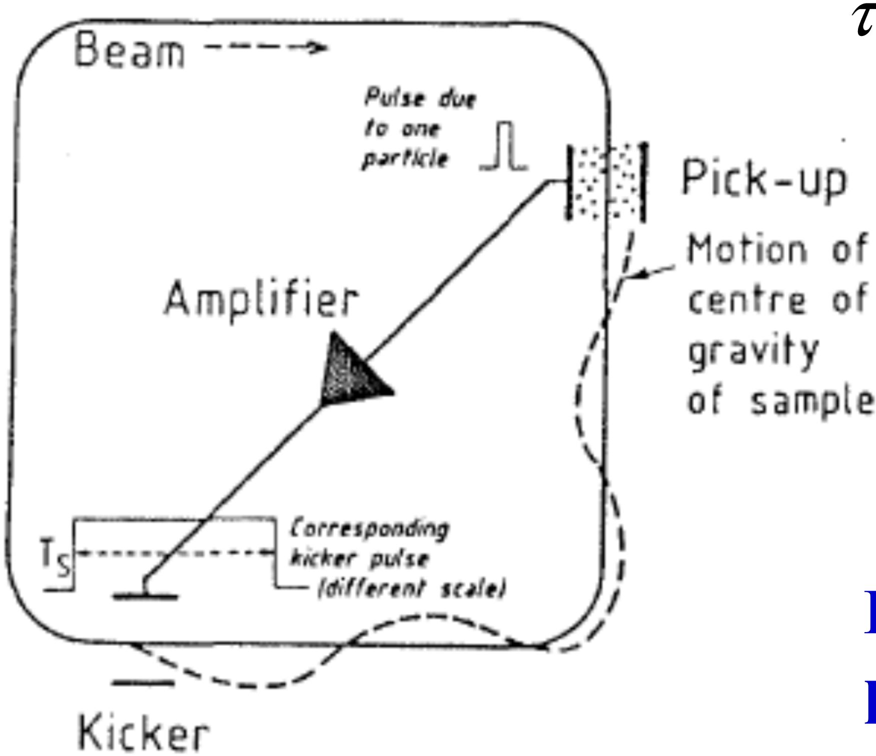


Replace an empty sub-ensemble with the one containing particle(s)→reduce the volume of phase space containing particles →reduce beam emittance (if a single charge: 1.6 ×10^{-19} Coulomb can be detected by Maxwell's demon, it is negative feedback)

Transverse Stochastic Cooling System

D. Möhl : CERN/PS/85-8(LEA)

$$\frac{1}{\tau} = \frac{W}{2N}\left[2g(1-\tilde{M}^{-2}) - g^2(M + U/Z^2)\right]$$

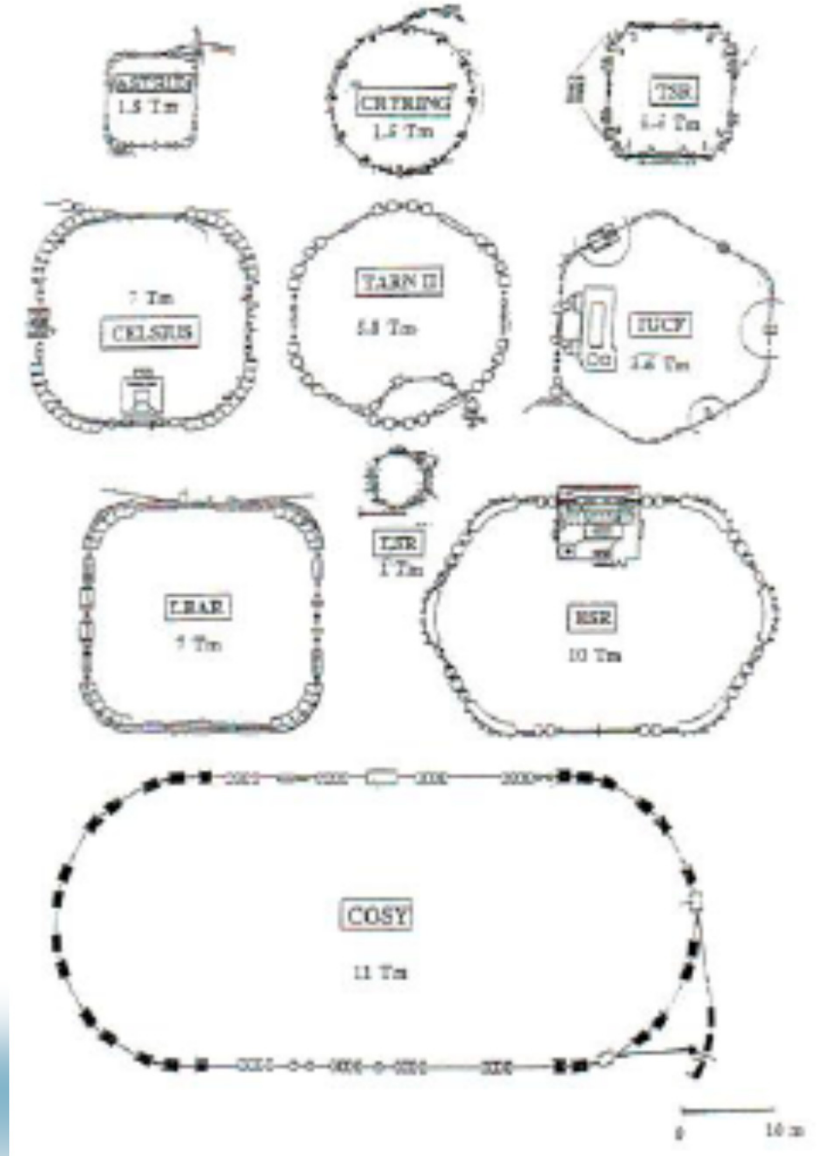


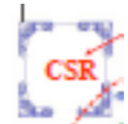
T_s=1/(2W)

N: No. of Particles in the beam
W: Bandwidth of cooling system
g: "gain" parameter (<1)
M **:Desired Mixing from kicker to PU**
$\tilde{M}$ **:Undesired Mxing from PU to Kicker**
U: Noize to signal ratio (U>0)
Z: charge number of the particle

Due to momentum spread, particles migrate between samples and this mixing continuously exchanges the sample populations.

Cooler Storage Rings in the World





CSR (C=35 m) to be operated at 2 K has stored $^{40}Ar^{+}$ ion beam (17, March, 2014)