Laser Cooling for 3-D Crystalline State at S-LSR

Presented by
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COOL05
The International Workshop on Beam Cooling & Related Topics

Contents

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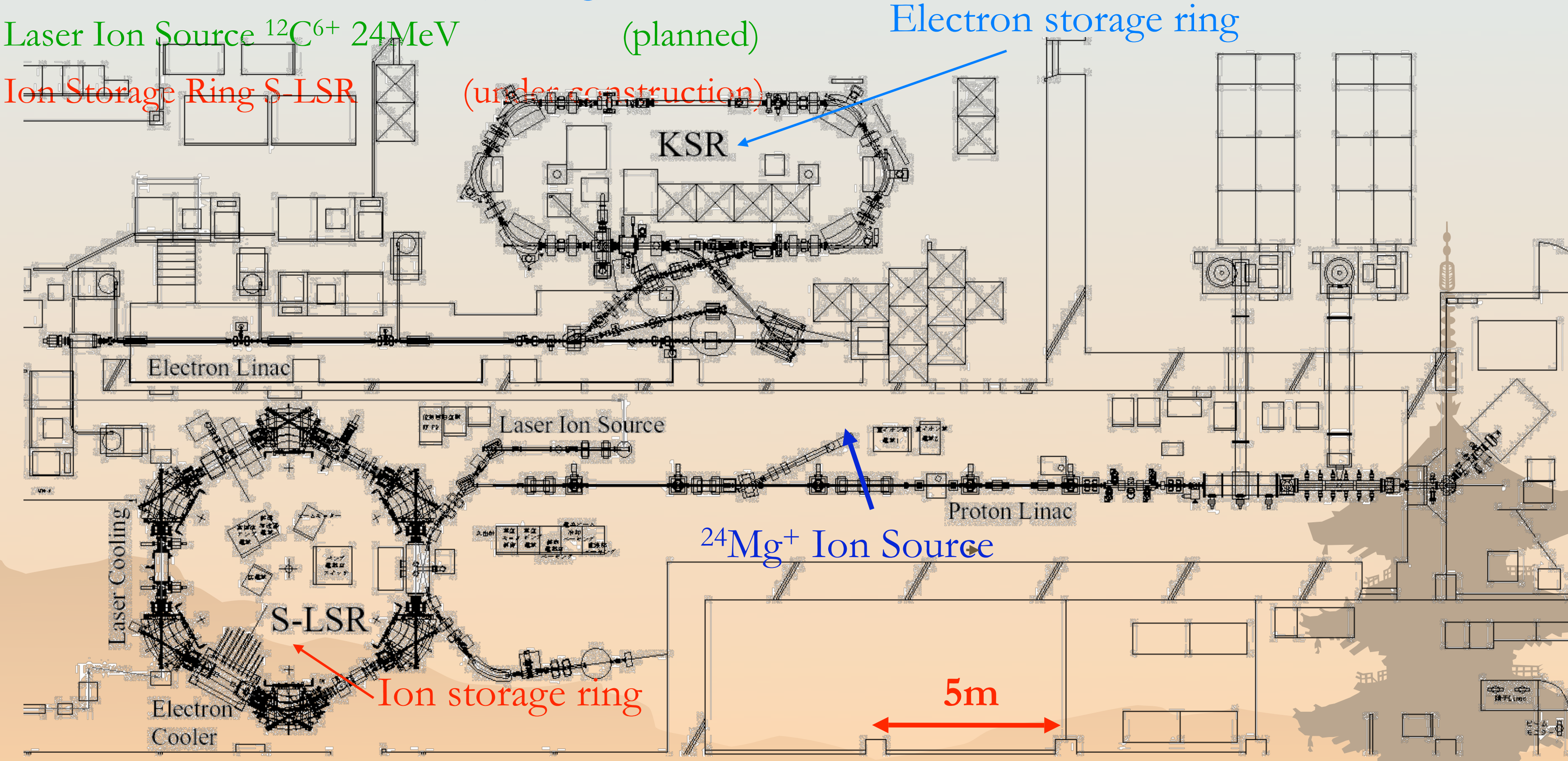
ION STORAGE AND COOLER RING, S-LSR

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 (under construction)

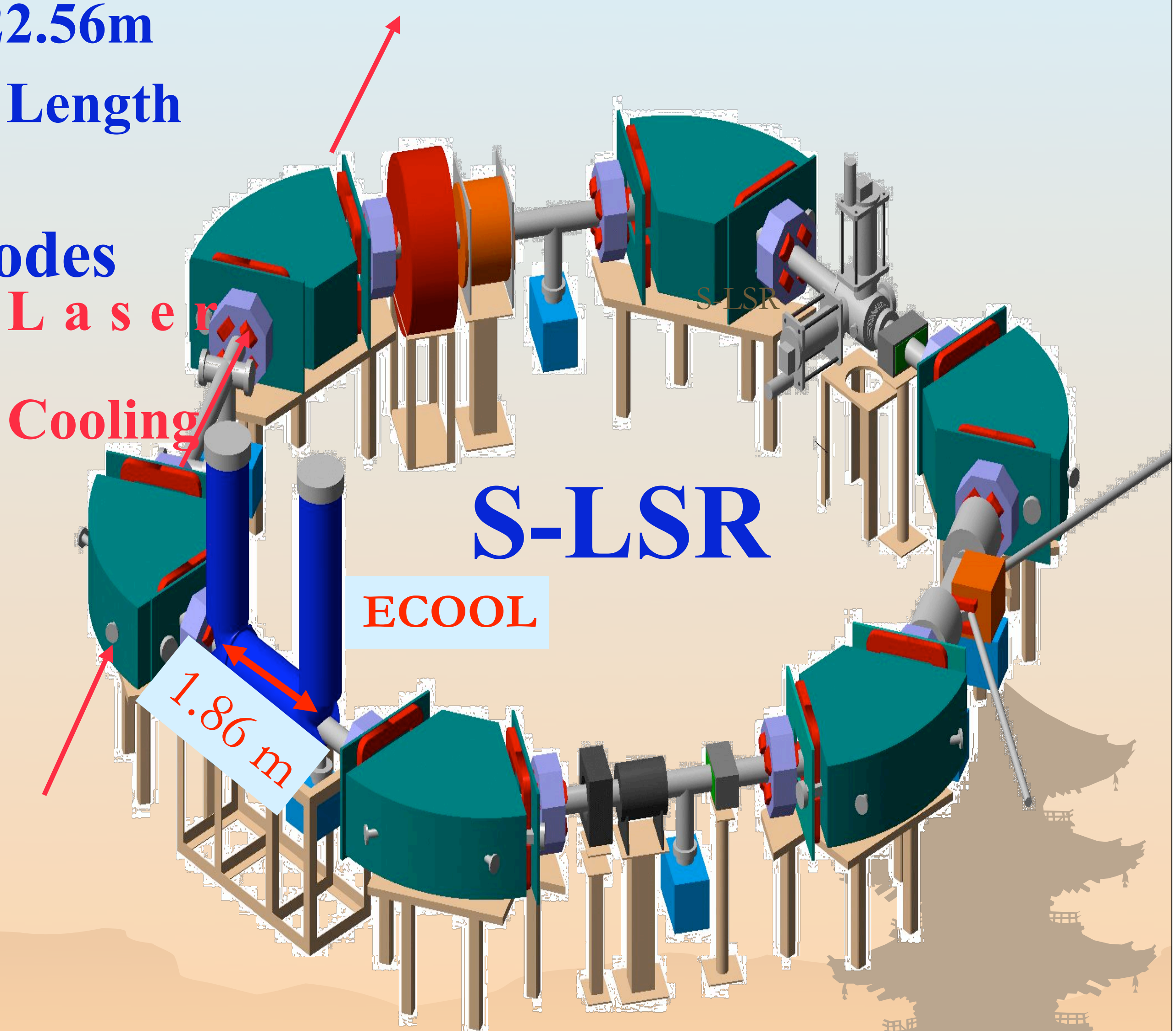
- Electron Cooler (under construction)
- $^{24}Mg^{+}$ Ion Source 35keV (existing)
- Laser Cooling for $^{24}Mg^{+}$ (planned)



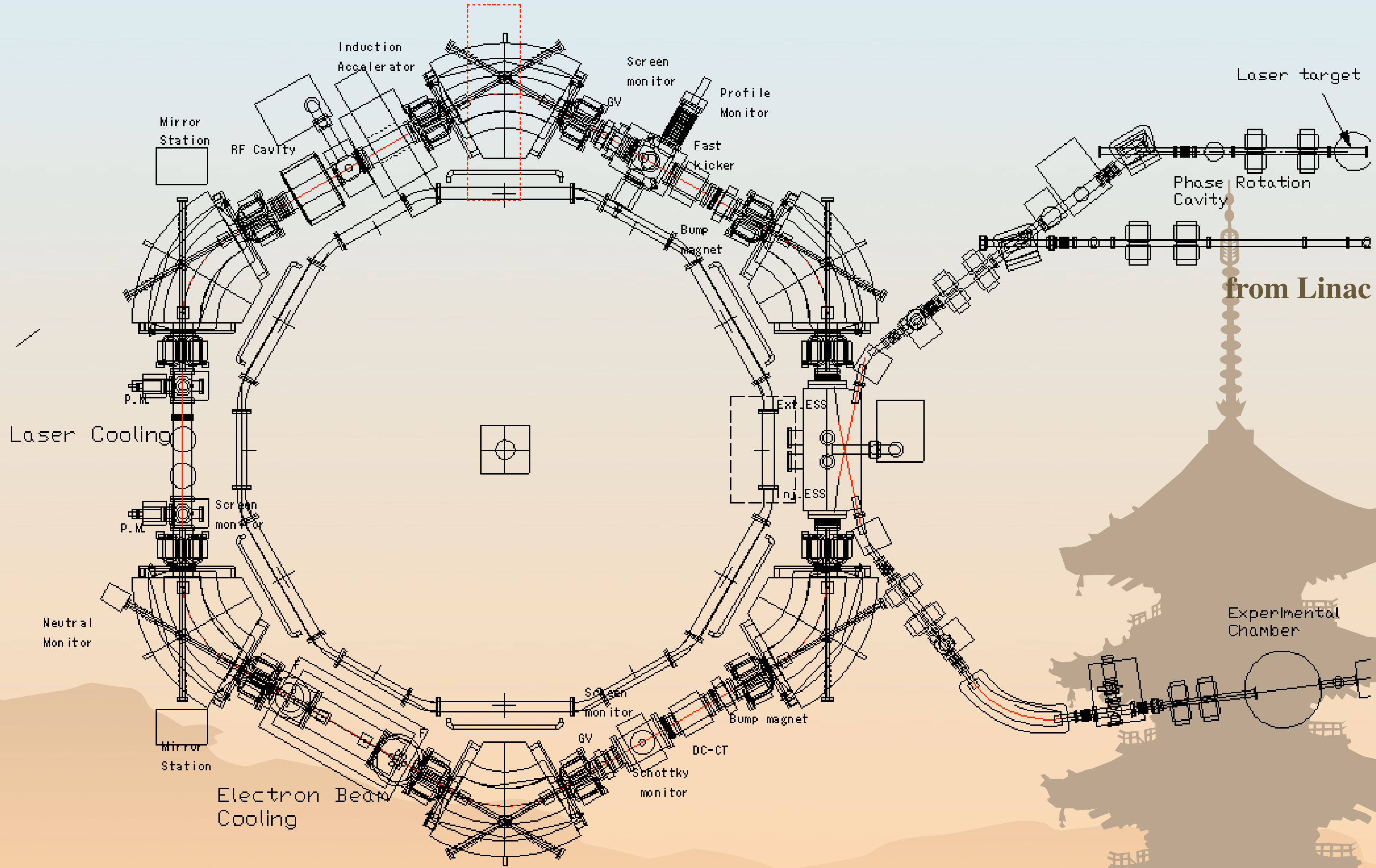
Main Parameters of S-LSR

Circumference	22.557 m
Average radius	3.59 m
Length of straight section	2.66 m
Number of periods	6
Betatron Tune	
Crystalline Mode	Normal Operation Mode
1.45 (H) , 1.44 (V)	1.872(H), 0.788 (V)
Bending Magnet	(H-type)
Maximum field	0.95 T
Curvature radius	1.05 m

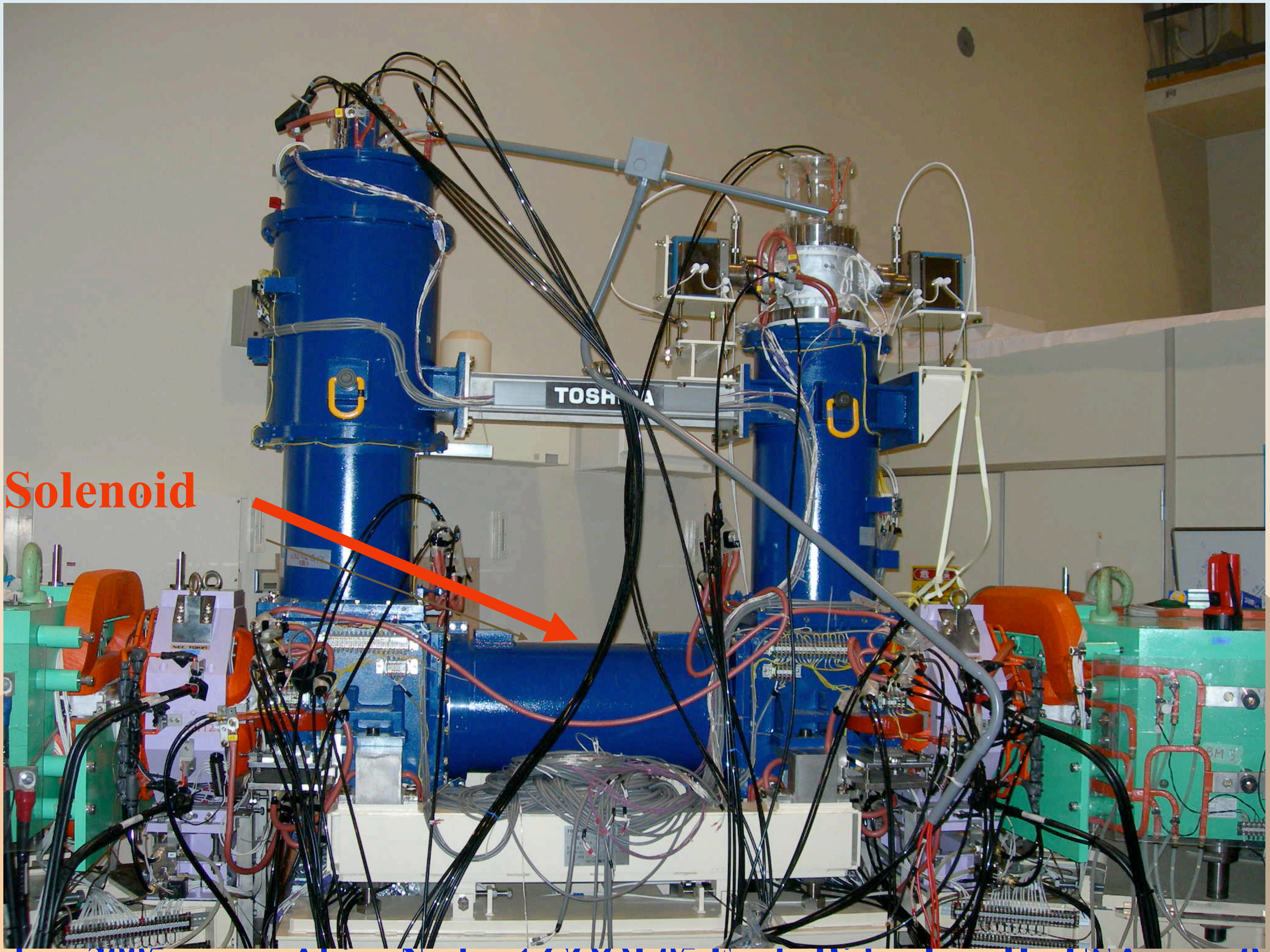
- **Compact Cooler Ring S-LSR**
  - Circumference 22.56m
  - Straight Section Length 1.86m
- **Two e-cooling modes**
  - Protons 7MeV (Ee=3.8keV)
  - $^{12}C^{6+}$ 2MeV/u (Ee=1.1keV)
- **Laser cooling**



Ring Layout

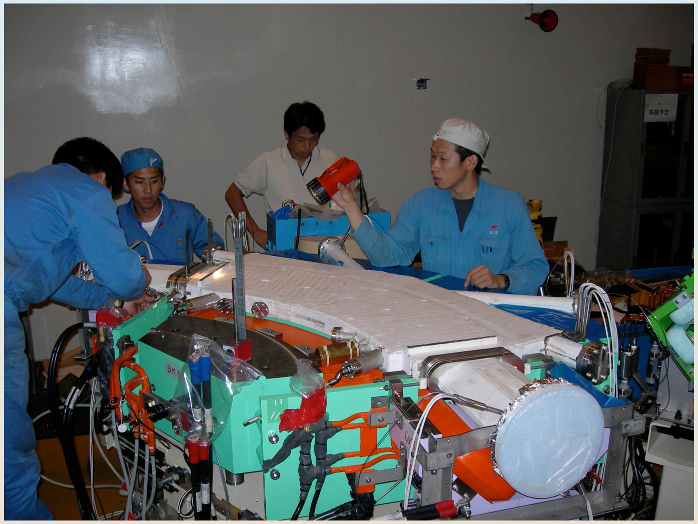

Induction
Accelerator
Screen
monitor
GV
Profile
Monitor
Fast
kicker
Mirror
Station
RF Cavity
Laser target
Phase Rotation
Cavity
from Linac
Bump
magnet
Ext. ESS
Inj. ESS
P.M
Laser Cooling
Screen
monitor
P.M
Neutral
Monitor
Experimental
Chamber
Screen
monitor
Bump magnet
GV
DC-CT
Schottky
monitor
Mirror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

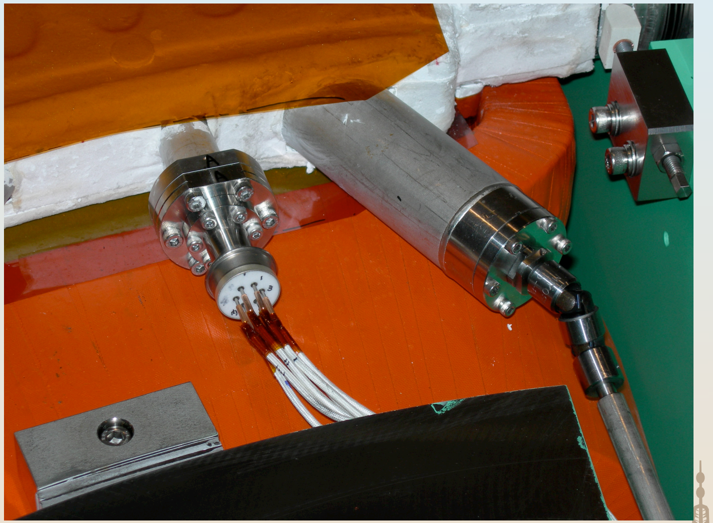
Coupling between horizontal and vertical directions is realized by the solenoid in the cooling section of the electron cooler

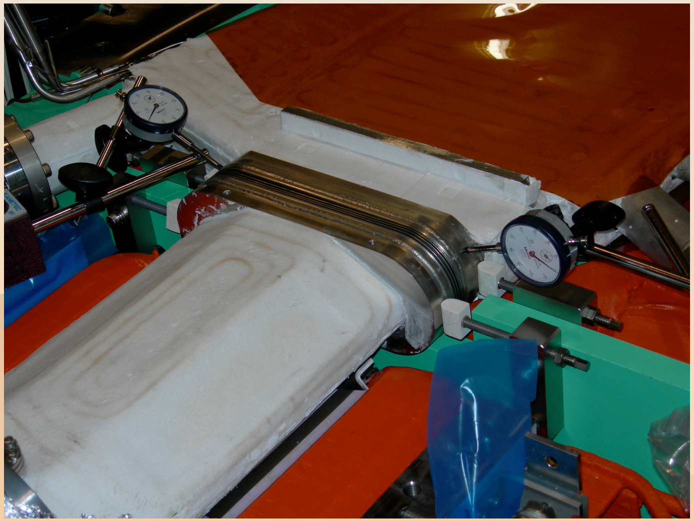


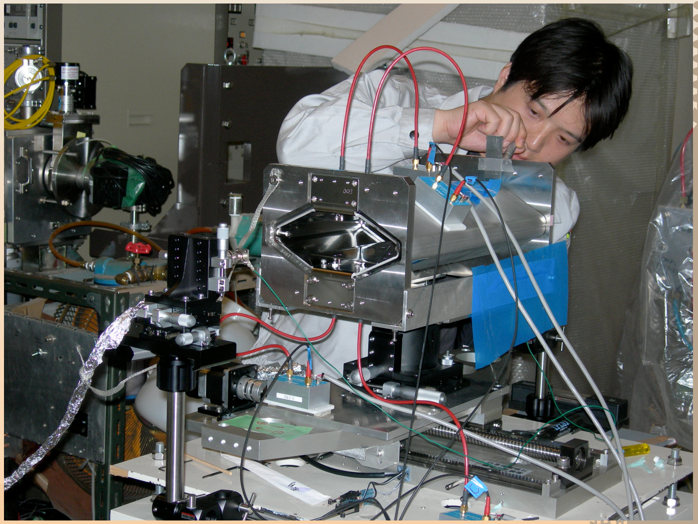
Cooler Solenoid

Installation of Vacuum Vessel into S-LSR

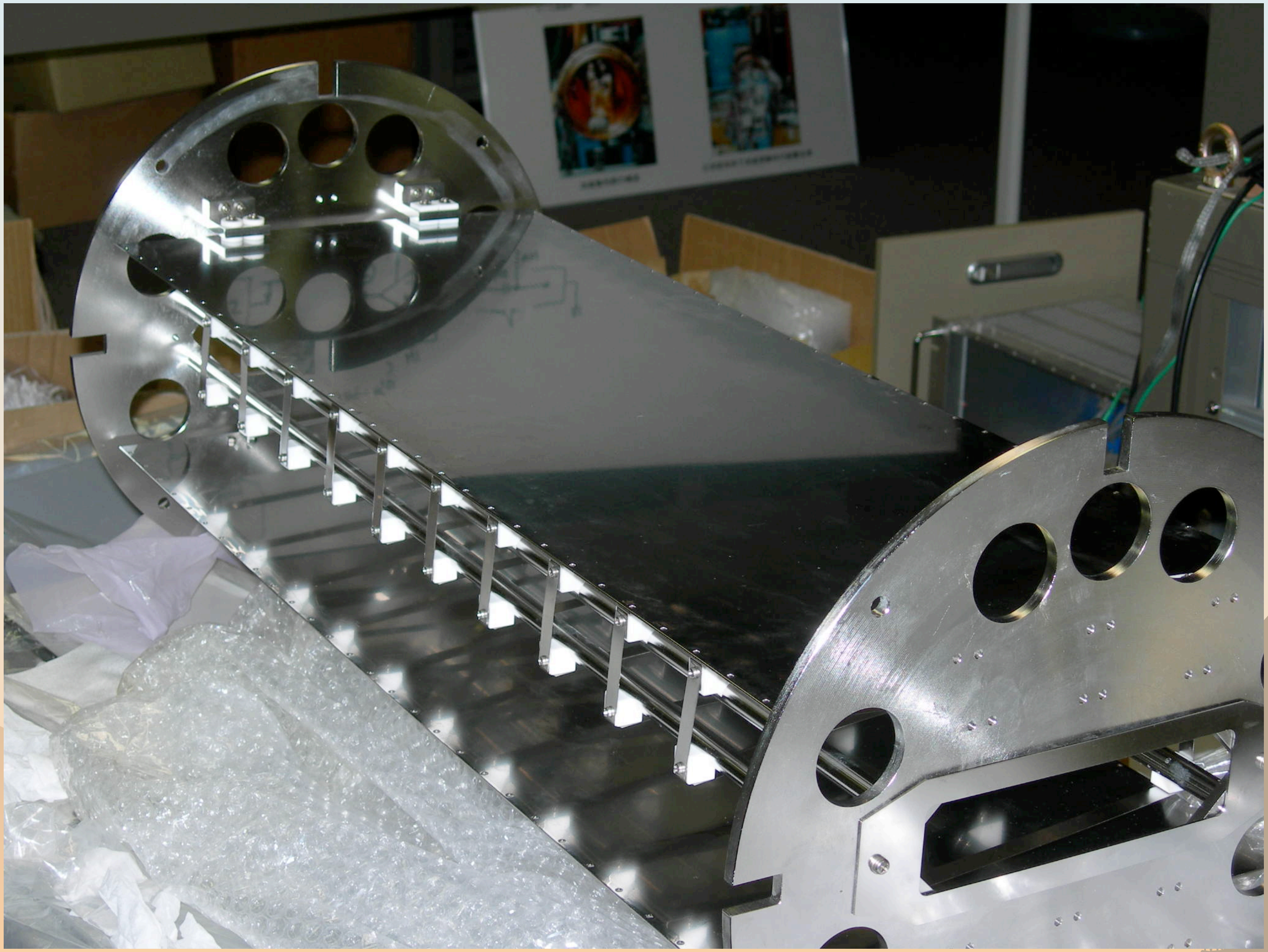






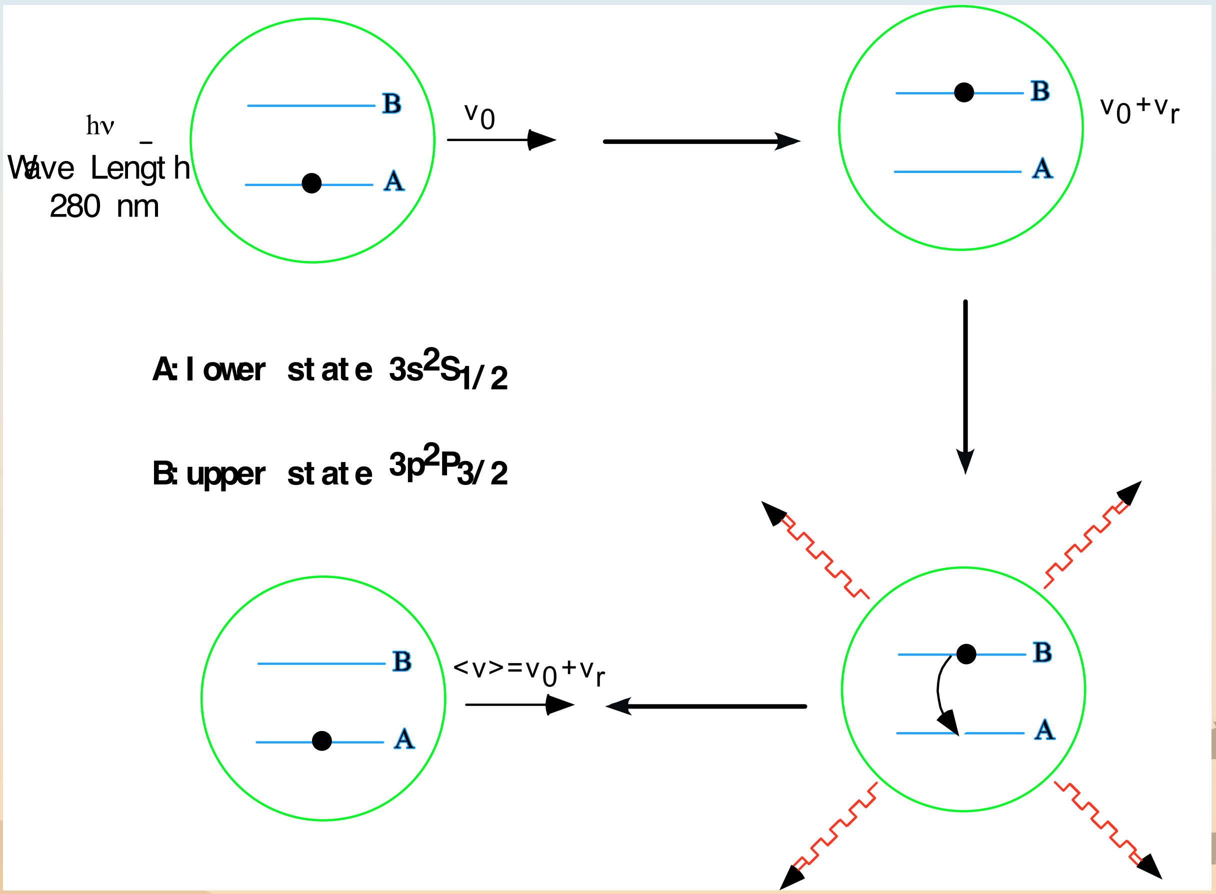


Schottky Pick-Up Moved from TARN II



2. LASER COOLING AT S-LSR

Principle of Laser Cooling (Longitudinal)



Laser Cooling at S-LSR

Main parameters for laser cooling for 3 ions

	$^{7}Li^{+}$	$^{9}Be^{+}$	$^{24}Mg^{+}$
T [ns]	43	8.2	3.5
Λ_0 [nm]	548	313	280
I_{sat} [mW/cm^2]	2.9	83	270

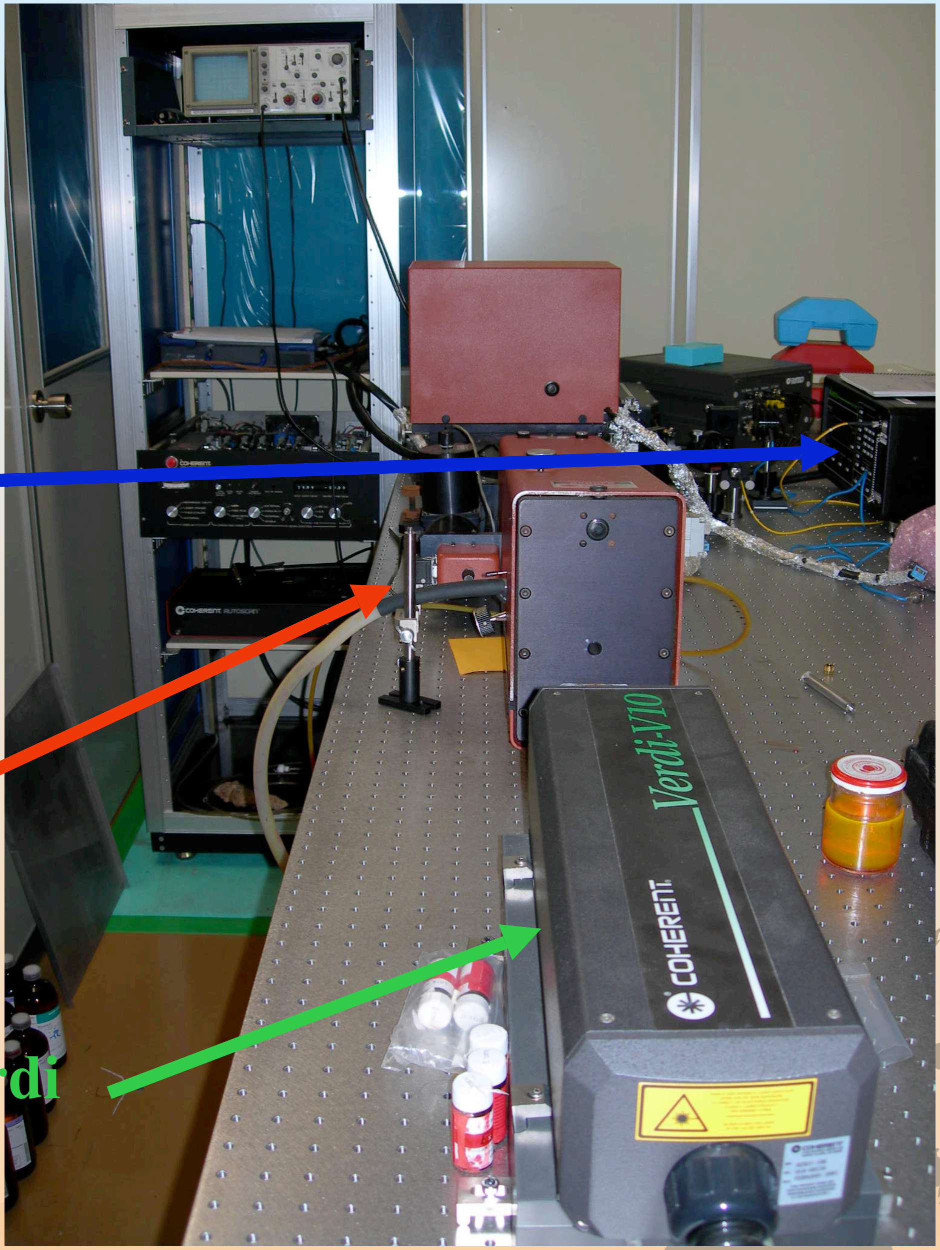
Ring dye laser with Rodamine 110 pumped by the solid state green laser. Verdi (532 nm) is to be applied

Ring Dye-Laser under Tuning

Second Harmonics Generator

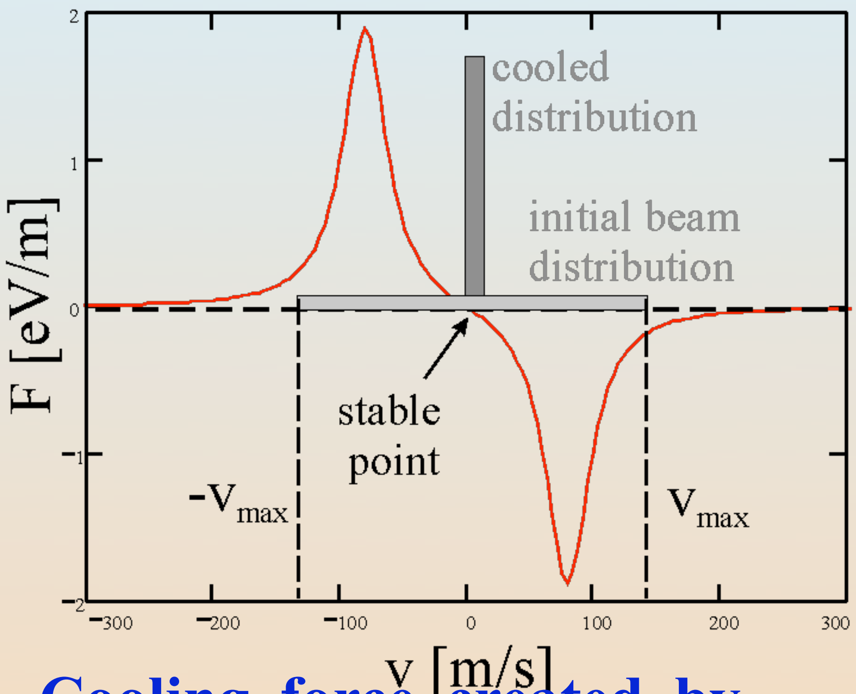
Ring Dye Laser

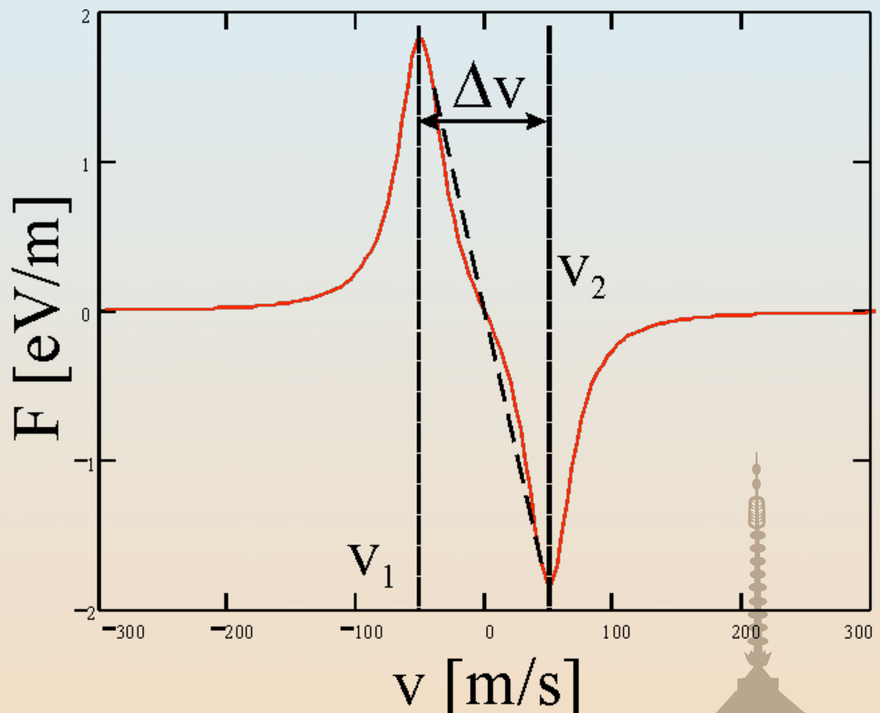
Green Laser Verdi



Cooling Time

65 μs=40 turns | **18 μs=11 turns**





Cooling force created by two counter propagating lasers.

The laser cooling force modified for fast cooling time by narrowing the distance between the positions of the maximum and minimum of the cooling force.

3. APPROACH TO 3-D CRYSTALLINE BEAM FOR DIFFERENT LATTICESTRUCTURES OF S-LSR

History of Approach to Crystalline Beam

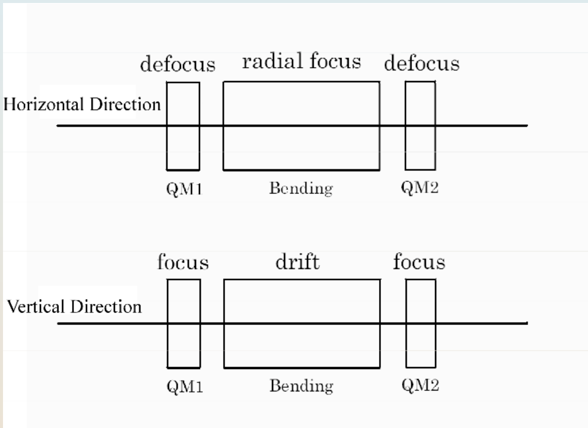
1. V.V. Parkhomchuk, Physics of Fast Electron Cooling, Proc. of ECOOL1984, 1984, pp.71-83.--- 1D ordered state for electron cooled proton at NAPM
2. M. Steck et al., Hyperf. Int. 99, 1996, pp245---1D ordered state for electron cooled heavy ions at ESR
3. H. Danared, A. Källberg, K.-G. Rensfelt, and A. Simonsson, Phys. Rev. Lett. 88, 174801 (2002)---1D ordered state for electron cooled heavy ions at CRYRING
4. T. Schaetz, U. Schramm and D. Habs, Crystalline ion beams, Nature, 412, 717(2001) ---3D crystalline state for $^{24}Mg^{+}$ with 1eV at PALLAS

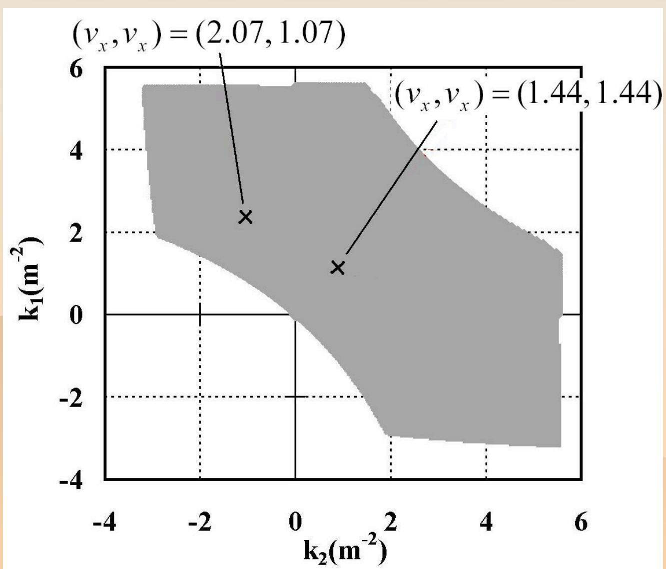
---Normal Lattice with Finite Dispersion---

By T. Shirai & M. Ikegami

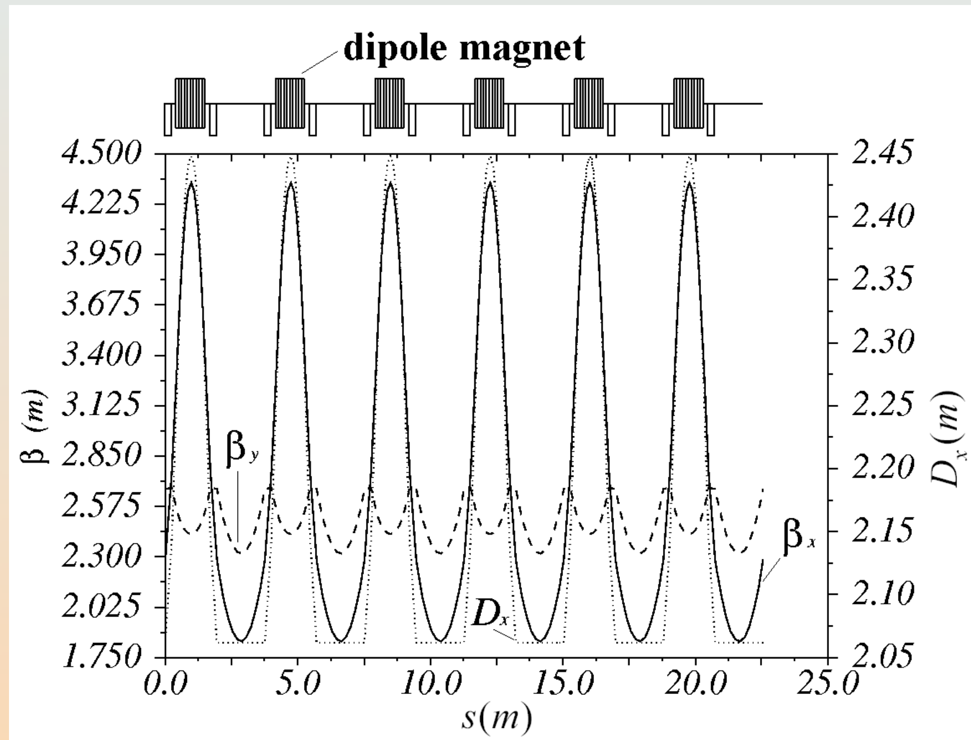
Lattice Parameters of S-LSR

Only Magnetic Field



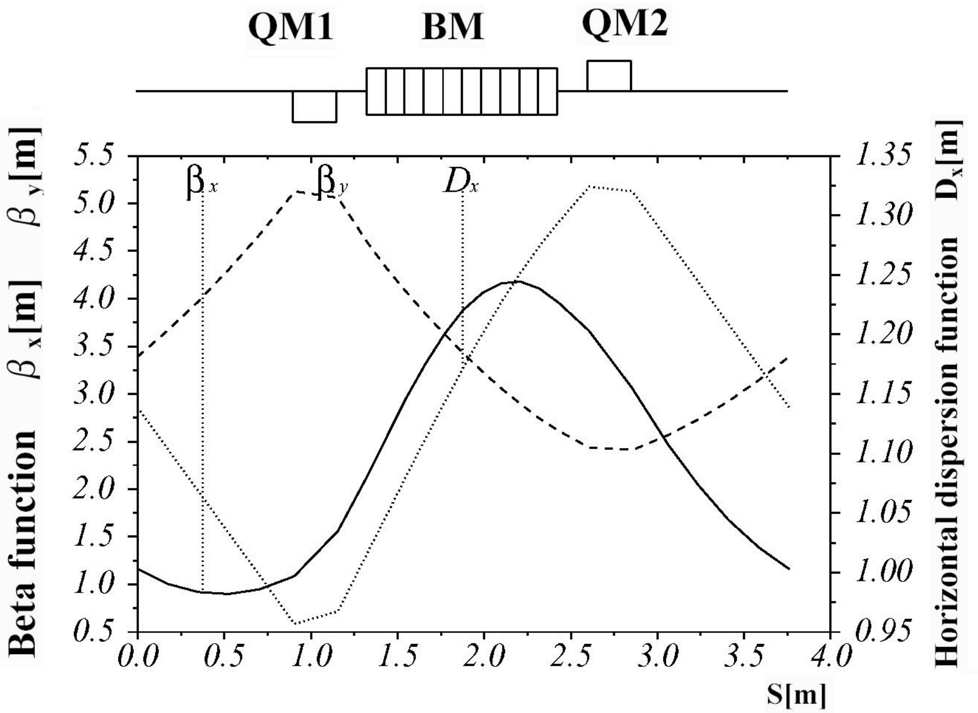


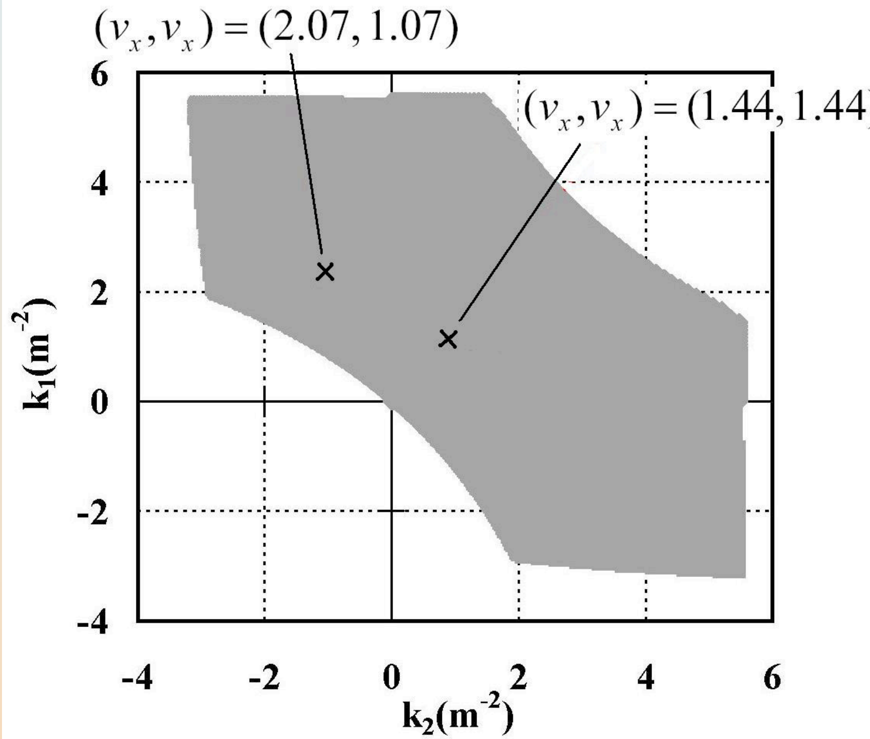
β-function, Dispersion
Betatron tune=(1.44,1.44)



Satisfies $\Delta\mu<\pi/2$, but needs coupling cavity

Normal Mode (No Electric Field)





β-function, Dispersion
Betatron tune=(2.07, 1.07)

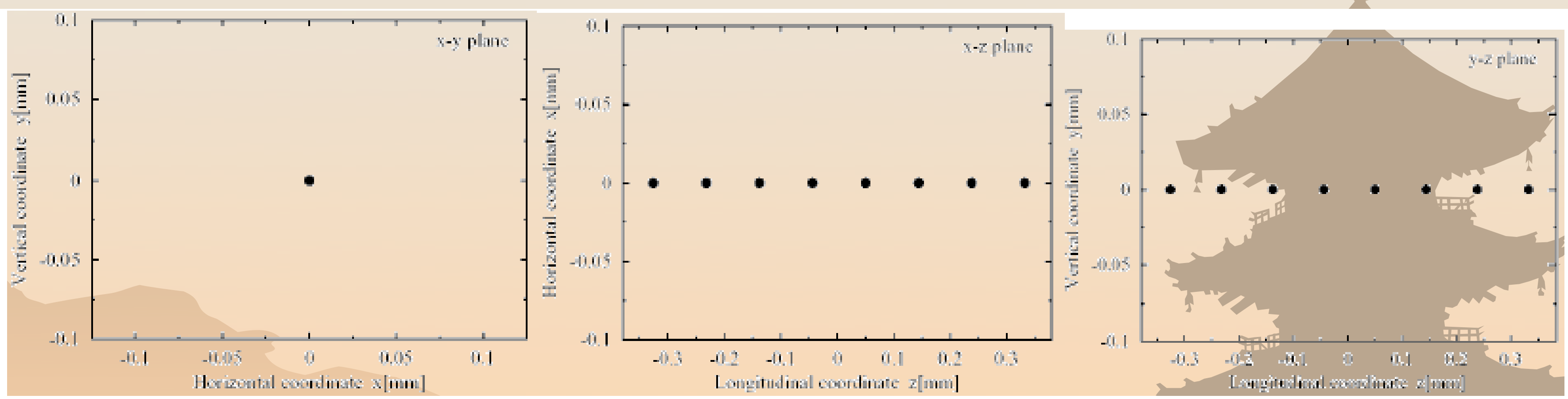
MD simulation of the magnetic mode

Coasting beam **Betatron tune (2.06, 2.06)**

Cooling force **Linear friction model**

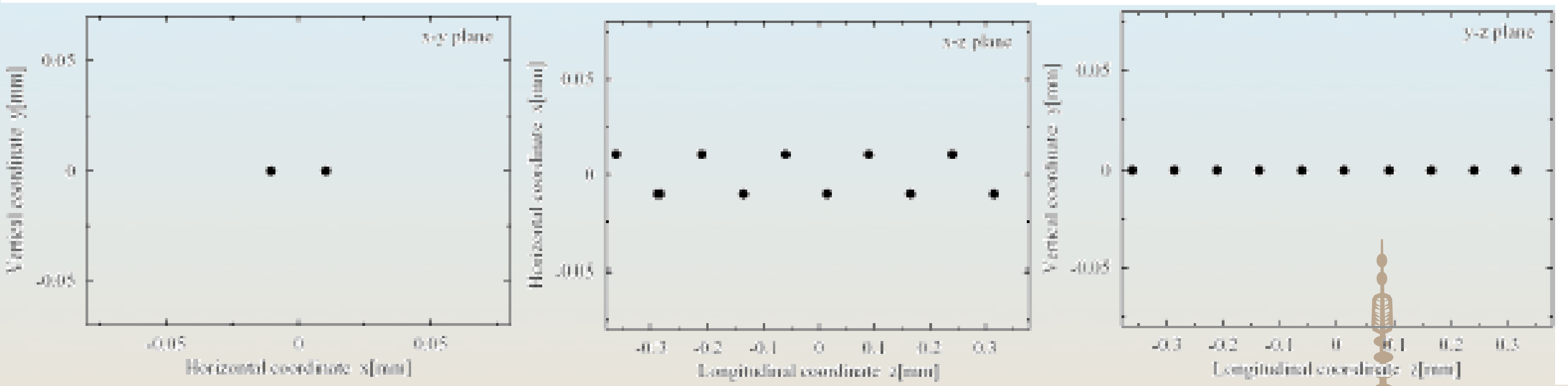
$$\ddot{a}\left(\frac{\ddot{A}p}{p_0}\right) = -f_s \frac{\ddot{A}p}{p_0}$$

λ=0.484



λ=normalized line density

λ=0.605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y-z plane
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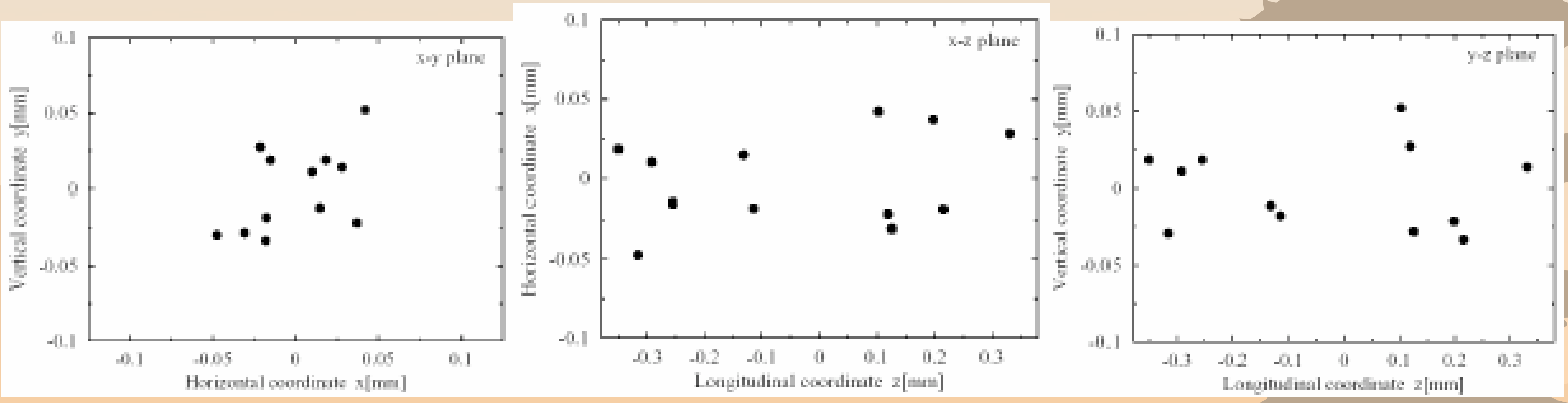
Longitudinal coordinate z[mm]

λ=0.726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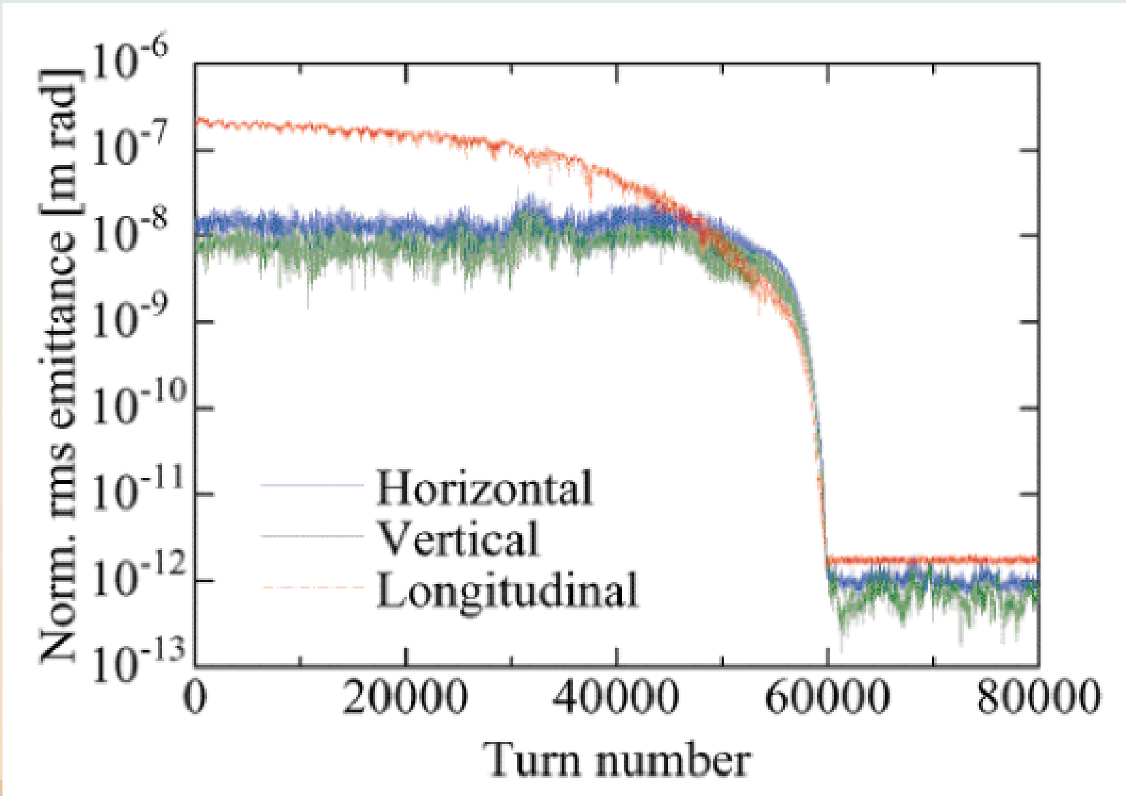
Horizontal coordinate x[mm]
Longitudinal coordinate z[mm]
y-z plane
Vertical coordinate y[mm]
Longitudinal coordinate z[mm]

By Hiromi Okamoto

3D Laser Cooling at S-LSR



Very fast 3D laser cooling achieved by the *resonant coupling method*;
H. Okamoto, et al, PRL 72, 3977(1994), H. Okamoto, PRE 50, 4982 (1994)

Y. Yuri and H. Okamoto

P.R.L. 93, (2004) 204801

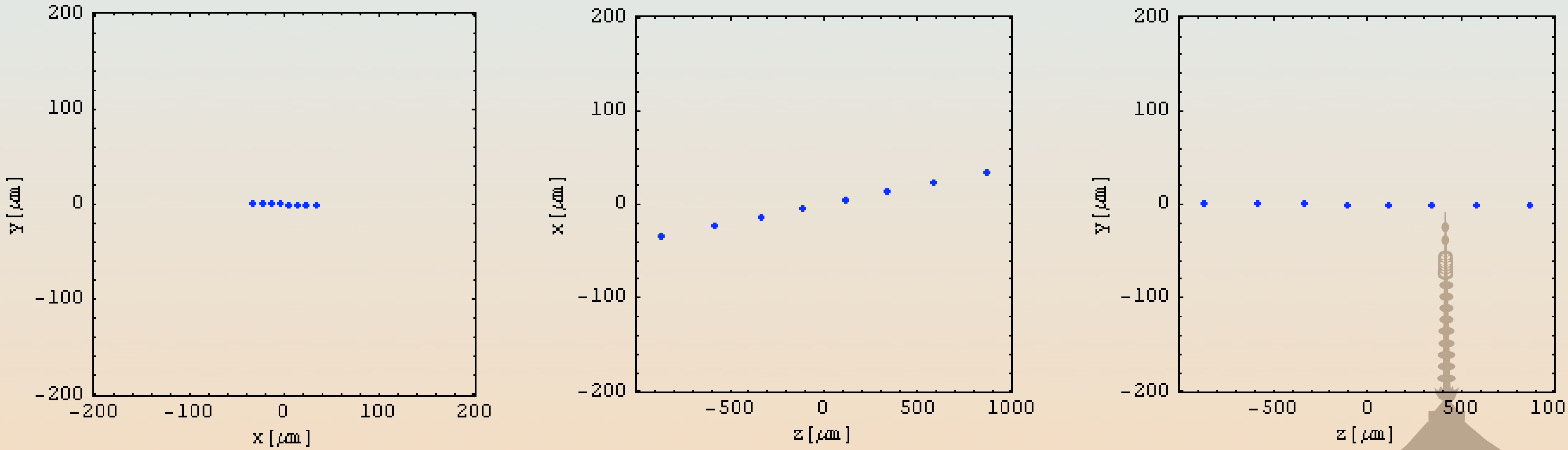
Simulation Parameters

Ion Species	$^{24}Mg^{+}$
Kinetic Energy of the Beam	35 keV
Superperiodicity (without solenoid)	6
Bare betatron tunes (ν_x,ν_y)	(2.067,1.073)
RF harmonic number	100
Length of the Solenoid Magnet	0.8 m
Saturation Parameter (on-axis) S_0	1.0
Minimum laser spot size	5 mm
Particle Number	800
Coupling for Transverse Cooling	Resonant Coupling

Y. Yuri and H. Okamoto

P.R.L. 93, (2004) 204801

Crystal Simulation assuming Ideal Tapered Cooling



Tapered Cooling aims at the cooling of the ions to the energy dependent on their radial positions to compensate the orbit length difference in the bending section. $E=E_0+kx$ (k:constant)

Expected Attainment for This Lattice

1. 3-D Laser Cooling is expected only by setting RF cavity at one of the long straight sections
2. 1 D string is expected for lower line density
3. Multi-dimensional crystralline state further needs real tapered cooling

---Lattice without Linear Dispersion Utilizing Dispersion-Suppressor---

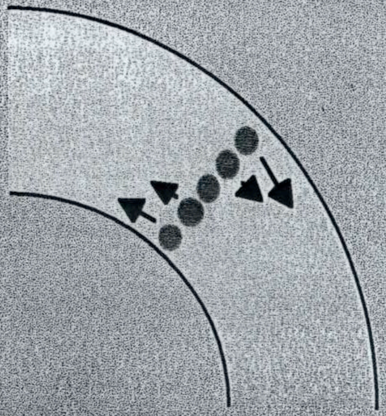
H. Okamoto

Shear-heating

Laser-cooling imposes constant *linear* velocity - beam ground state has a constant *angular* velocity.

$D_{cool} = 2.7$ m

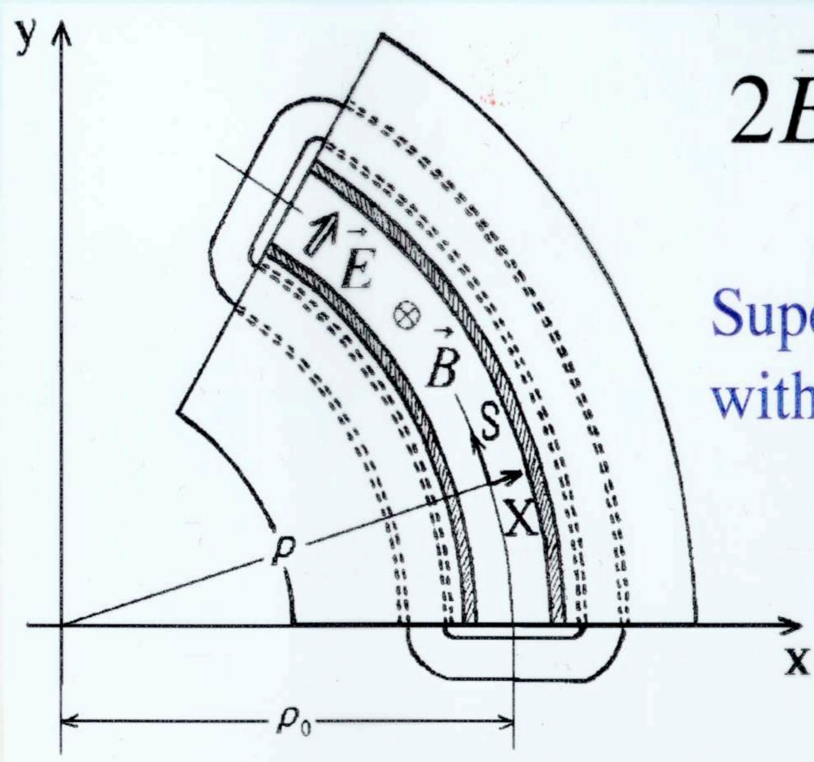
$\Delta x = 1$ mm => $\Delta v \sim 360$ m/s



This (possible) heating effect scales with beam size - does thus not imply constant density!

Lattice without Momentum Dispersion

(M. Ikegami et al. Phys. Rev. ST-AB. 7, 120101)



$$2\vec{E}(\rho_0) = -(\vec{v}_0 \times \vec{B})$$

Superposition of Electric Field with Magnetic Field

1] W. Hennelberg, Ann. D. Physik **19**, 335 (1934).

[2] W.E. Millett, Phys. Rev. **74**, 1058 (1948).

Equation of Motion of Charged Particle in Magnetic and Electric Fields

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

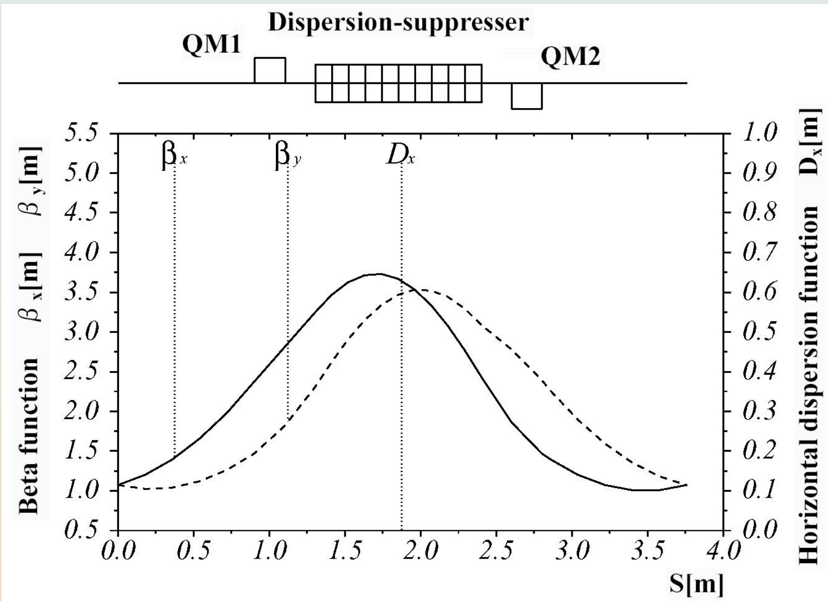
$$\frac{d^2x}{ds^2} + \frac{1-n}{\rho^2}x = \frac{1}{\rho}\frac{\Delta p}{p}$$ Magnetic Field

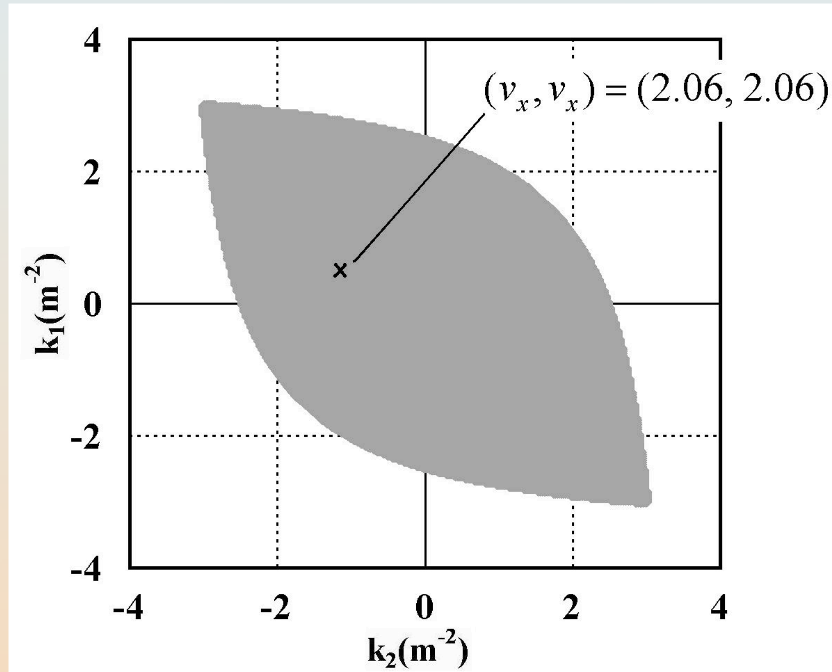
$$\frac{\Delta W}{W} = 2\frac{\Delta p}{p}$$

By M. Ikegami

Lattice Parameters of S-LSR

Magnetic Field superposed with Electric one





Radially constant electric field is asumed, although dependence of E (r)=k(const.)/r is expected by cylindrical electrodes. Adjustment wit Intermediate Electrodes is expected to be possible.

Hamiltonian for the Particles in the Storage Ring

Only Magnetic Field is Applied

$$H = \frac{1}{2}\left(p_x^2 + \nu_x^2 x^2\right) + \frac{1}{2}\left(p_y^2 + \nu_y^2 y^2\right) + \frac{1}{2}\left(p_s^2 + \nu_s^2 s^2\right) + \frac{1}{\rho} x p_s$$

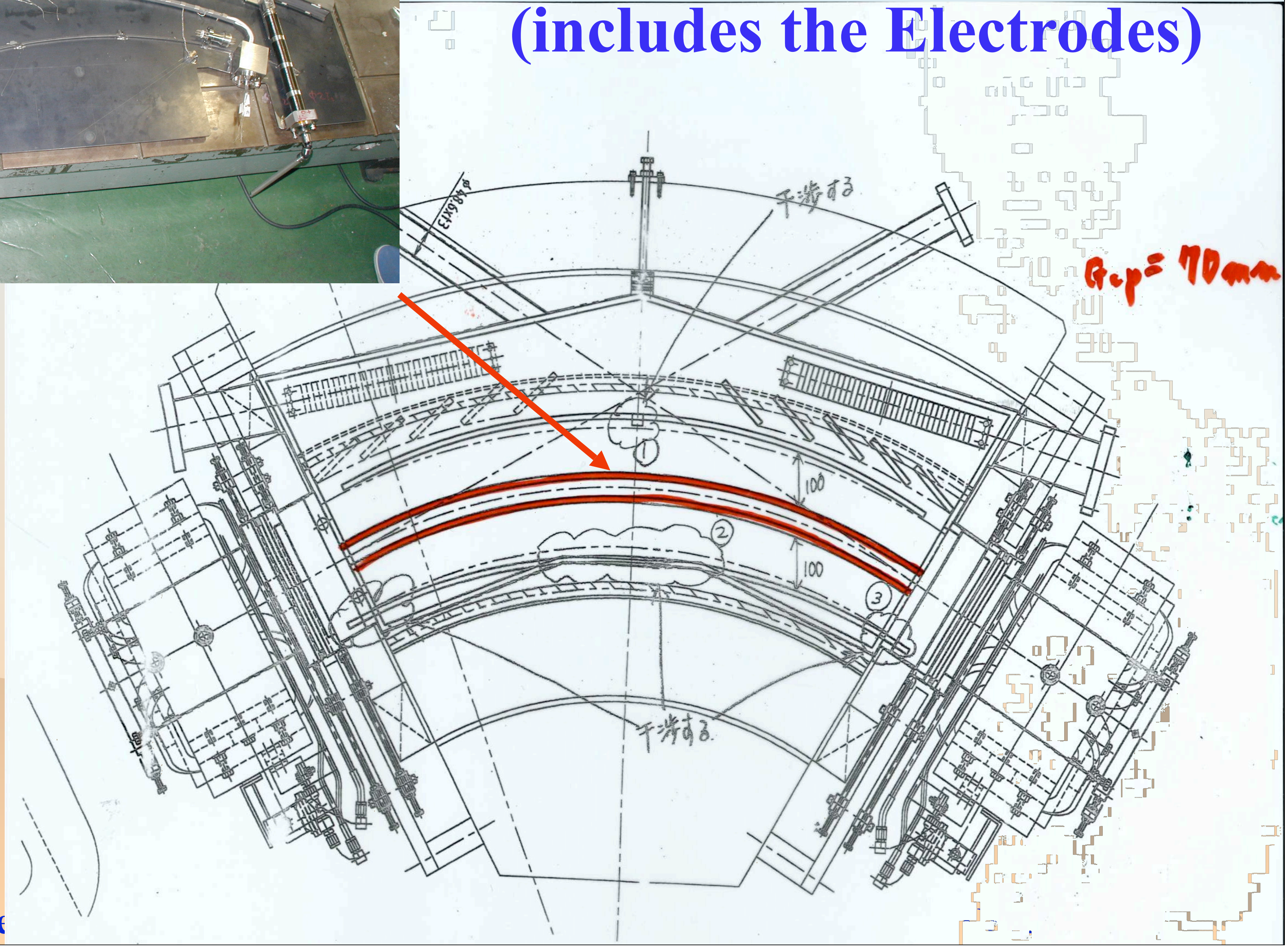
↑
Linear Dispersion

Electric Field is superposed with the Magnetic Field

$$H = \frac{1}{2}\left(p_x^2 + \nu_x^2 x^2\right) + \frac{1}{2}\left(p_y^2 + \nu_y^2 y^2\right) + \frac{1}{2}\left(p_s^2 + \nu_s^2 s^2\right) + \left(1 - \frac{qV_0}{\beta_0^2 E_0}\right)\frac{1}{\rho} x p_s$$

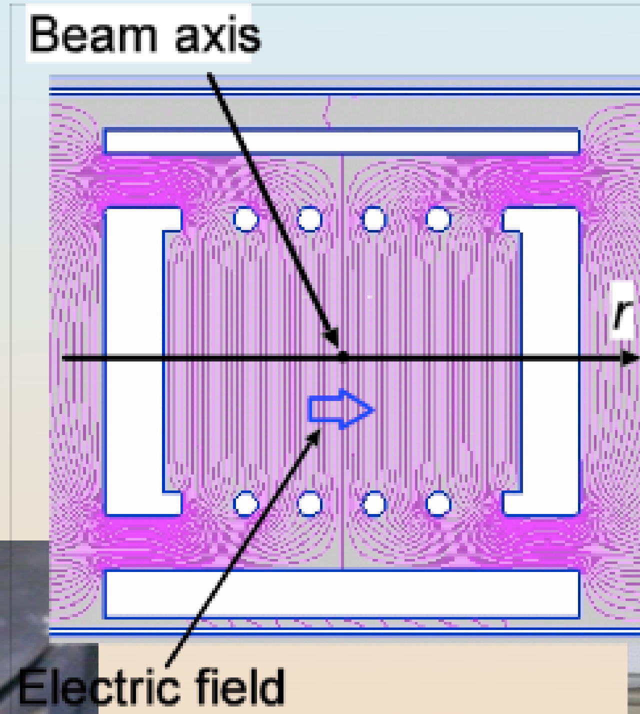
↑
This term vanishes if $2E_0 = B_y v_0$

Vacuum Chamber in the Magnet Section (includes the Electrodes)

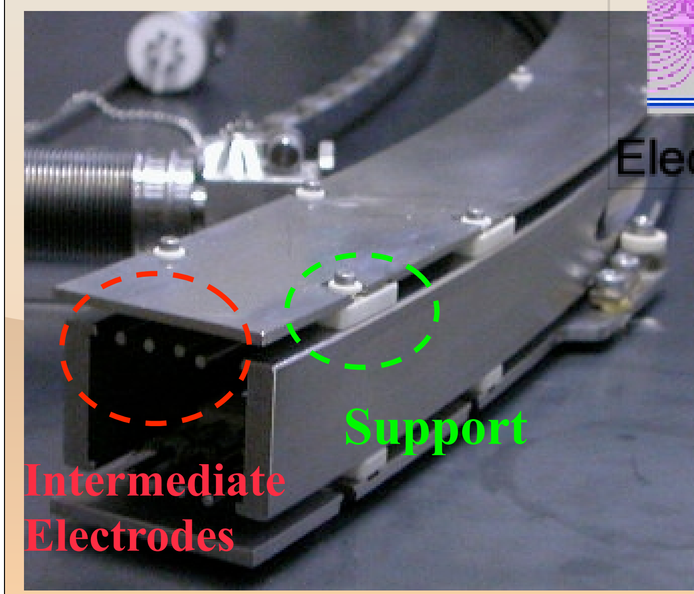


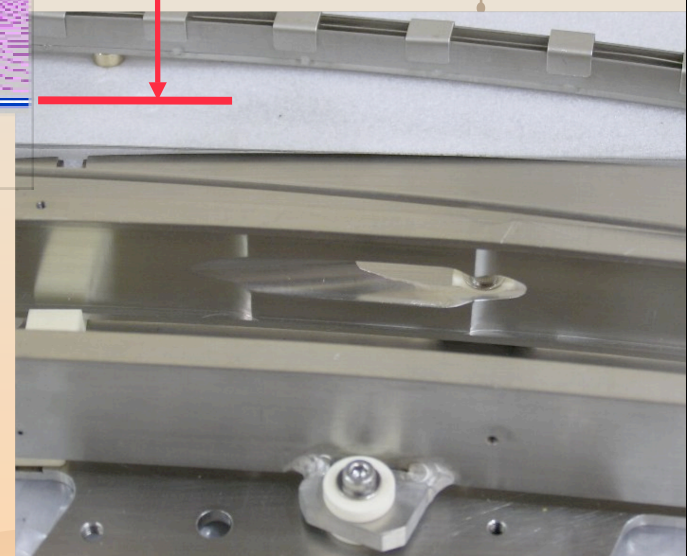
By M. Tanabe and M. Ikegami

Electric Field to be inserted into the Dipole Magnet



Chamber Height :45 mm
in Magnet Gap of 70 mm

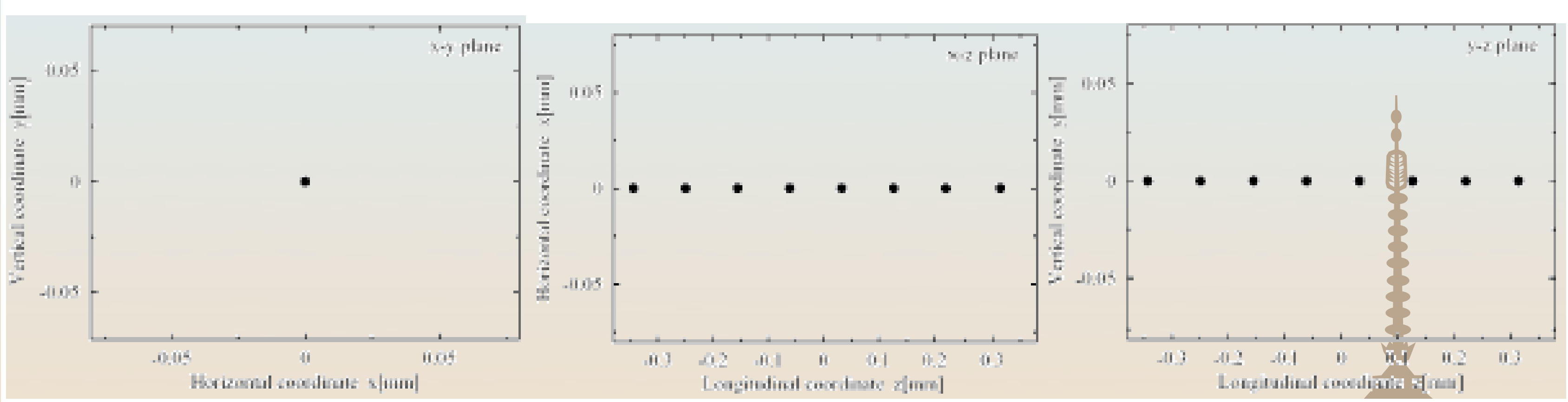




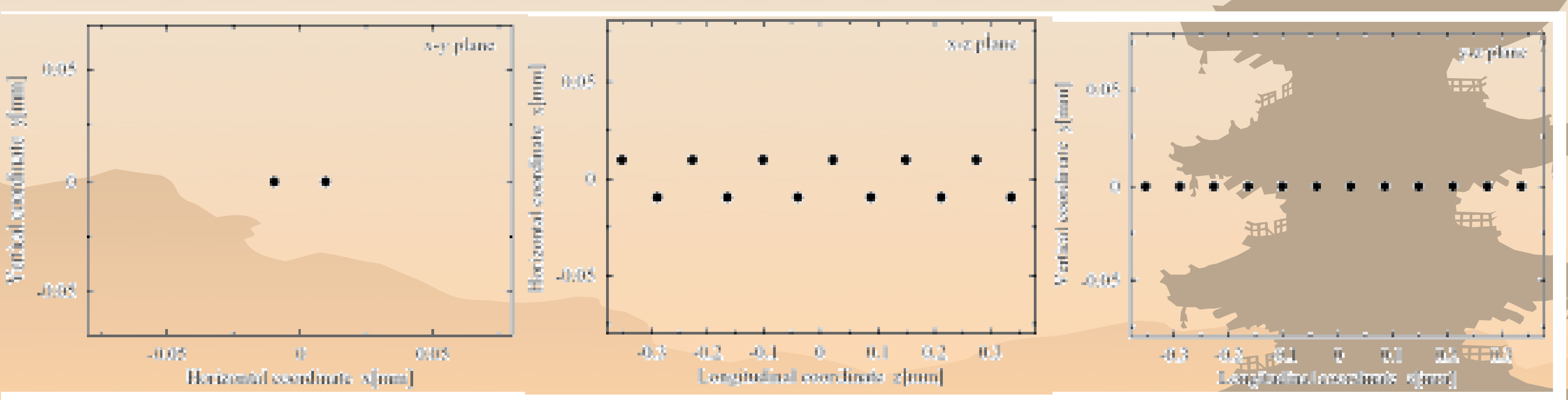
Simulation of the dispersion-free mode

Coasting beam   betatron tune (2.06, 2.06)

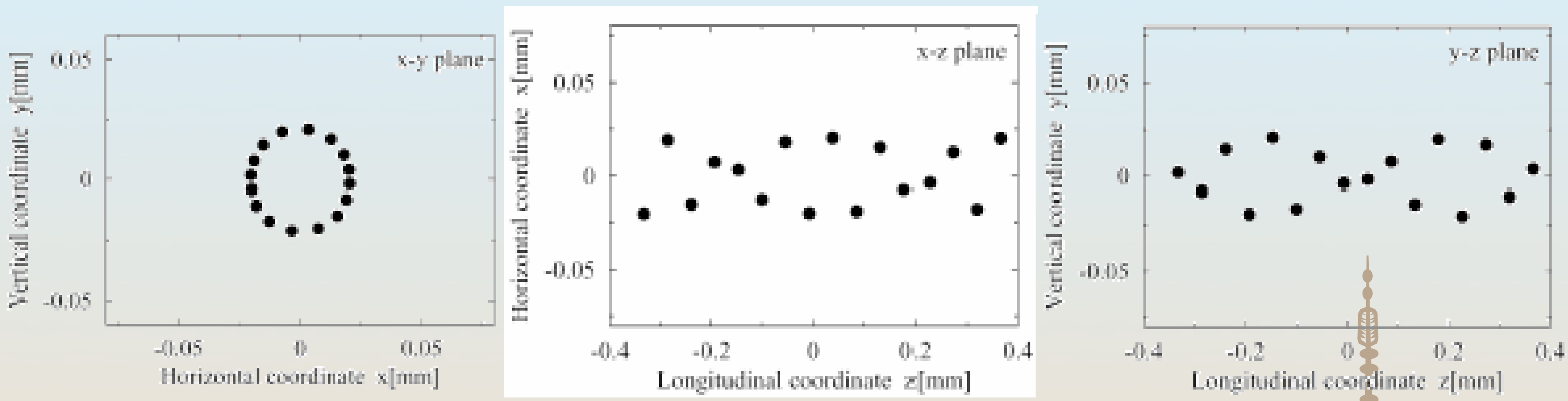
λ=0.484



λ=0.726



λ=0.975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Horizontal coordinate x[mm]
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-0.05
-0.4
-0.2
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0.4
Longitudinal coordinate z[mm]
y-z plane
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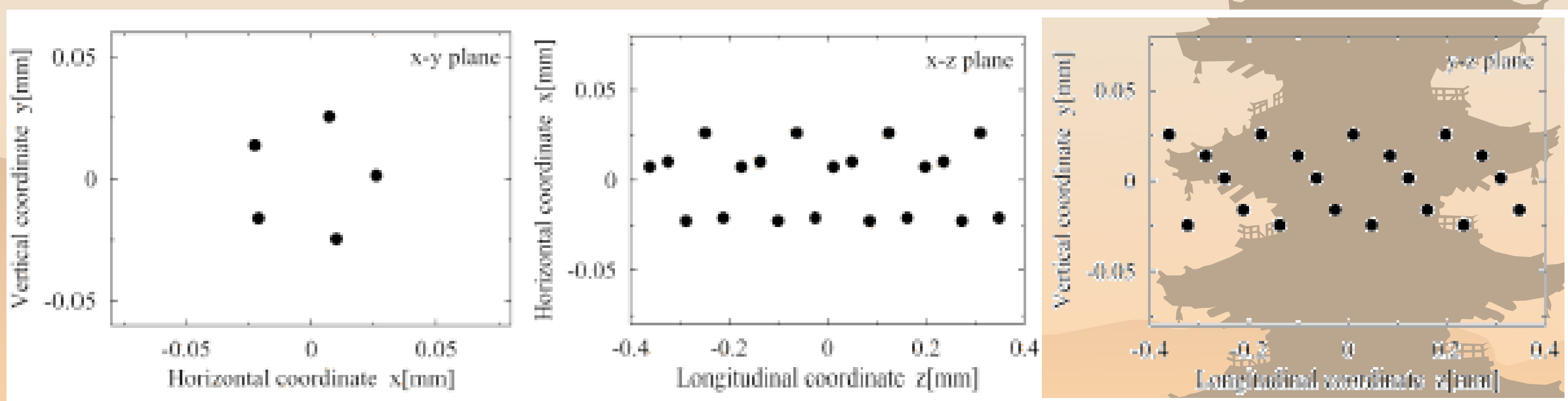
Longitudinal coordinate z[mm]

λ=1.22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Horizontal coordinate x[mm]
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0
-0.05
-0.4
-0.2
0
0.2
0.4
Longitudinal coordinate z[mm]
y-z plane
Vertical coordinate y[mm]
0.05
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-0.05
-0.4
-0.2
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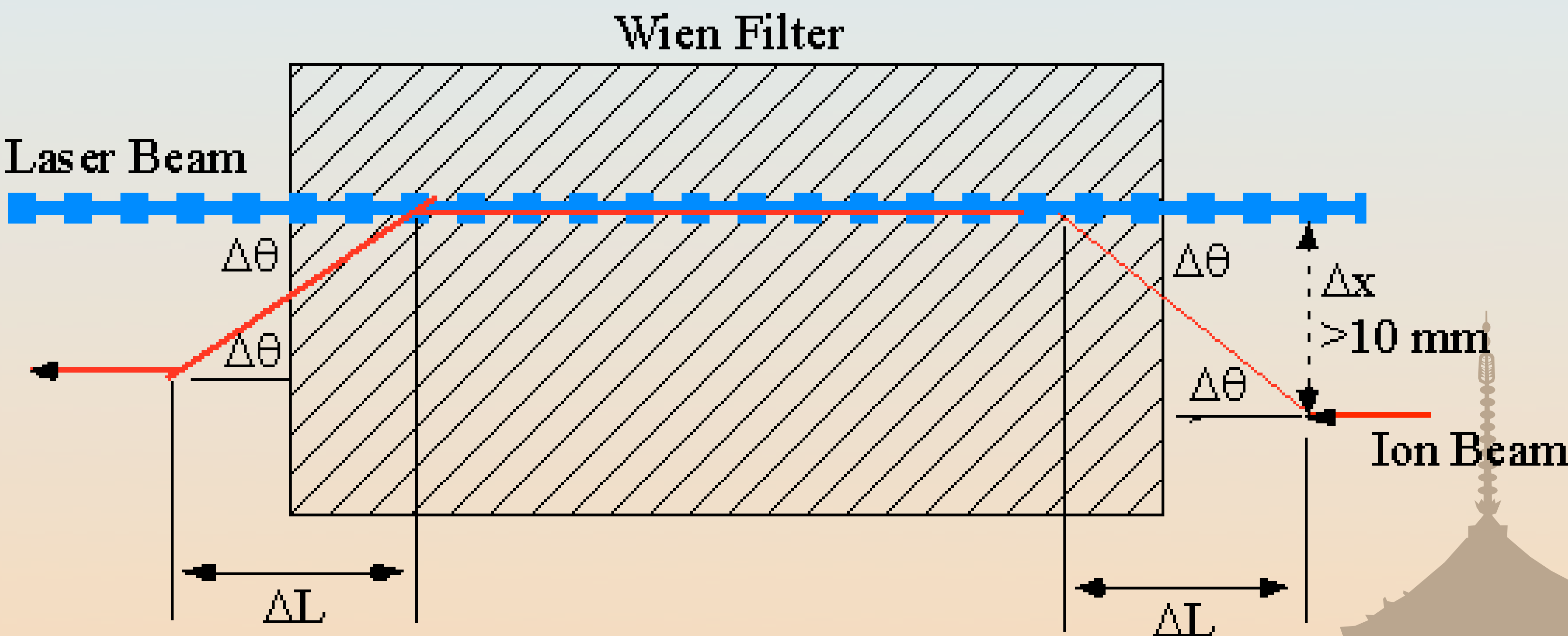
0.2
0.4
Longitudinal coordinate z[mm]

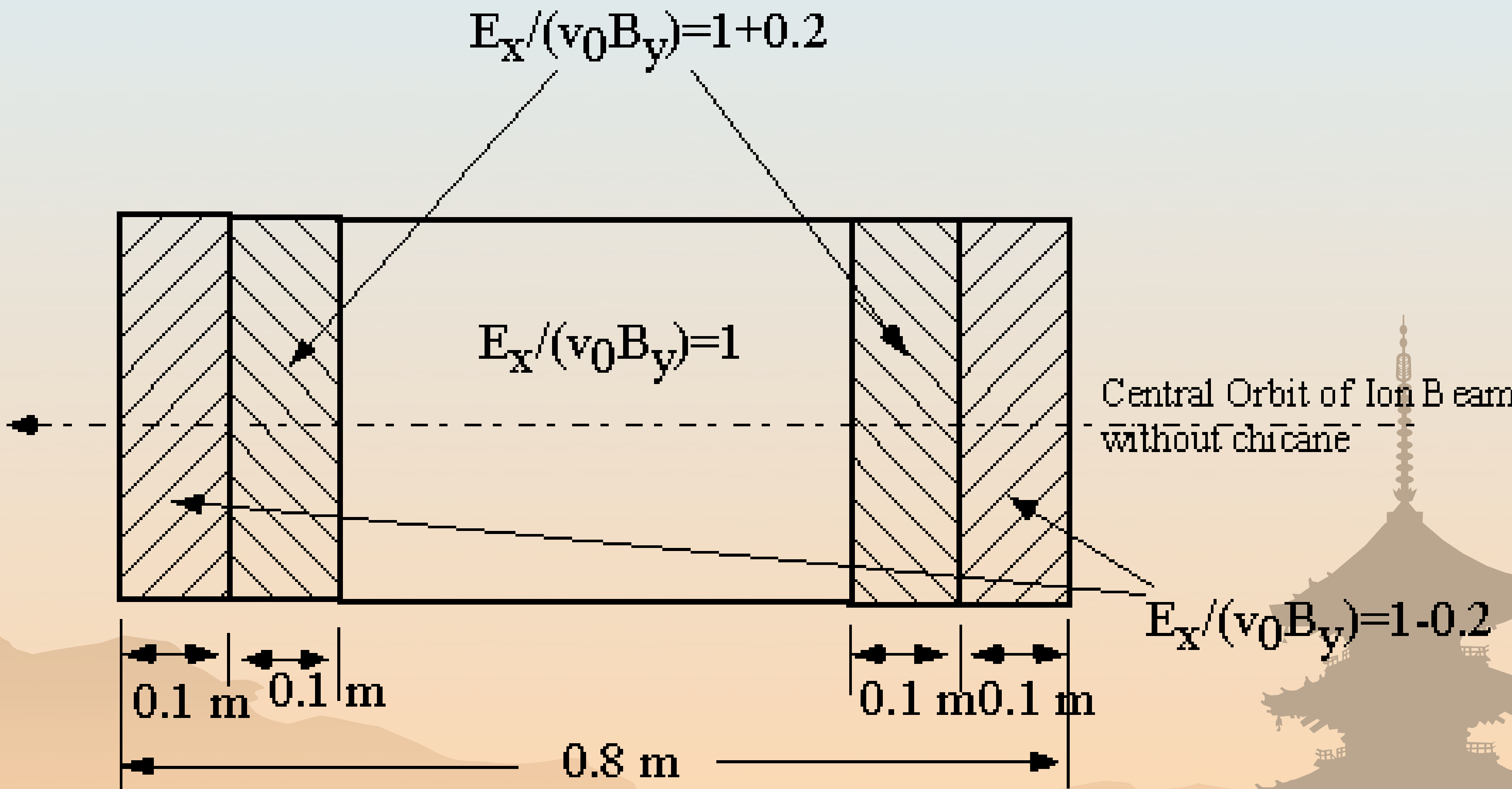
4. PROPOSAL OF TAPERED LASER COOLING

Tapered Laser Cooling by combination with a Wien Filter



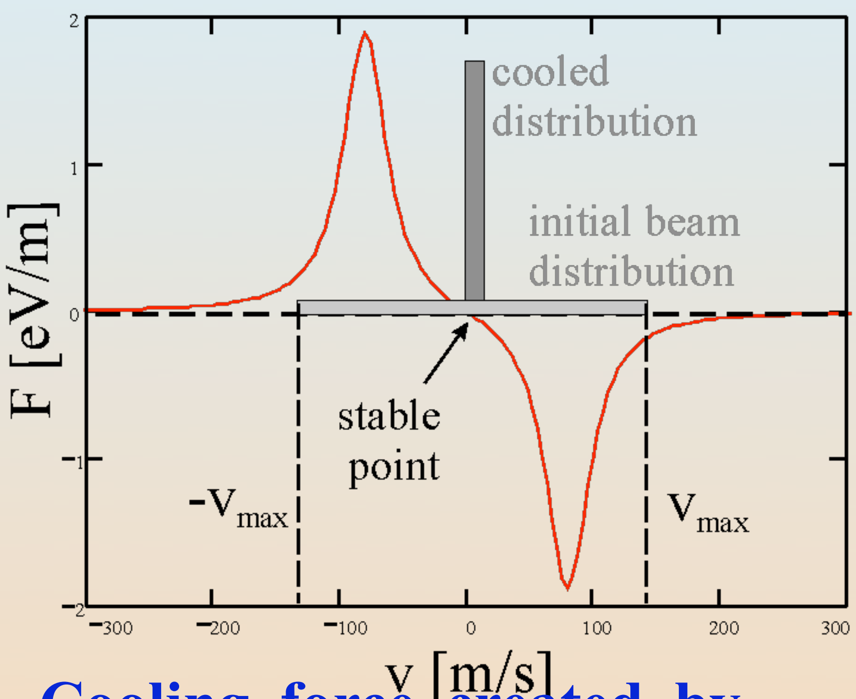
Orbit chicane is made to attain partial overlapping between ion beam and laser only inside the Wien Filter.

Creation of Chicane by Modulation of Magnetic Field Strength



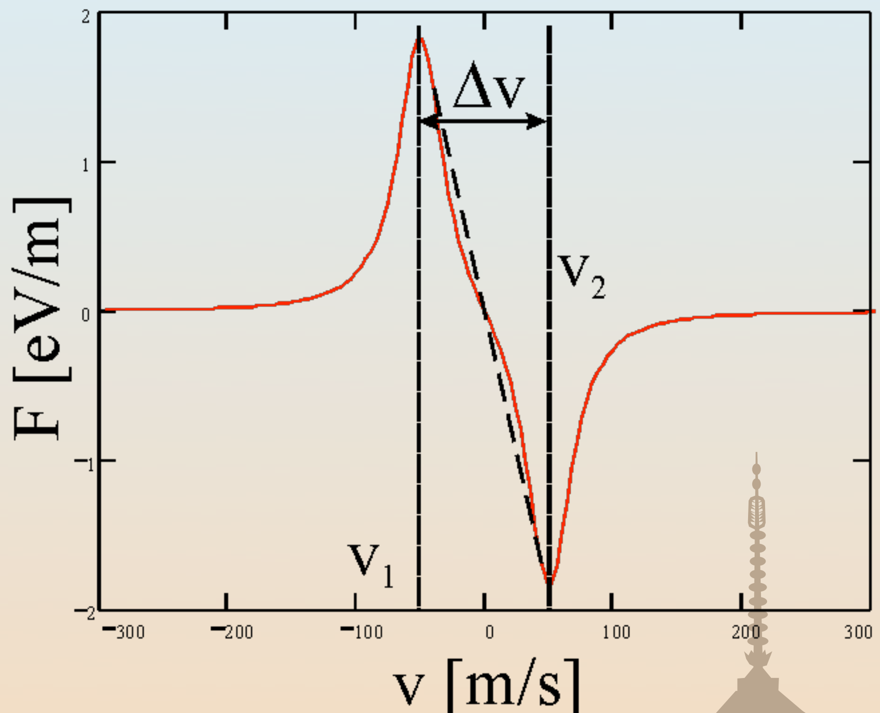
Cooling Time

65 μs=40 turns



Cooling force created by two counter propagating lasers.

18 μs=11 turns



The laser cooling force modified for fast cooling time by narrowing the distance between the positions of the maximum and minimum of the cooling force.

Tapered Rate for Single Cooling Section

$$\frac{v_0 + \Delta v}{v_0} = \frac{2\pi(\rho_0 + x) + 6L_s}{2\pi\rho_0 + 6L_s}$$

L_s: Length of long straight section

ρ_0: Radius of curcature at the central orbit

Summary

Plan for Experiments (still under discussion)

1. Normal Lattice ⟶ Operation tune of (1.44,1.44)

   Stable ($\Delta\mu<\pi/2$) but needs coupling cavity (difficult to fabricate)

   ⟶ Operation tune of (2.07,1.07)

   Synchro-betatron coupling is used for 3-D laser cooling

   1-D ordering is expected

2. Dispersion Free Lattice ⟶ Operation tune of (2.07,2.07)

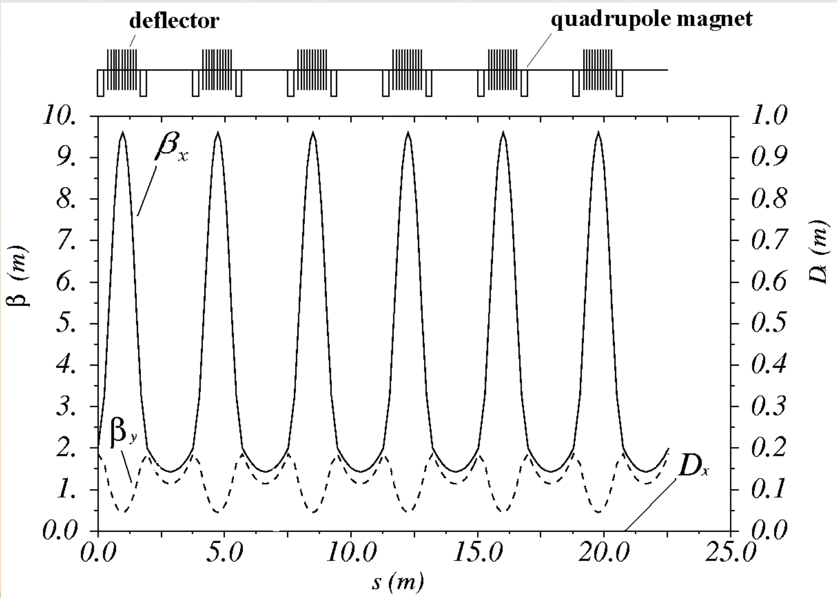
   Possibility of "Tapered Cooling" by Laser Cooling only inside of the Wien Filter ⟶ Violate maintenance condition?

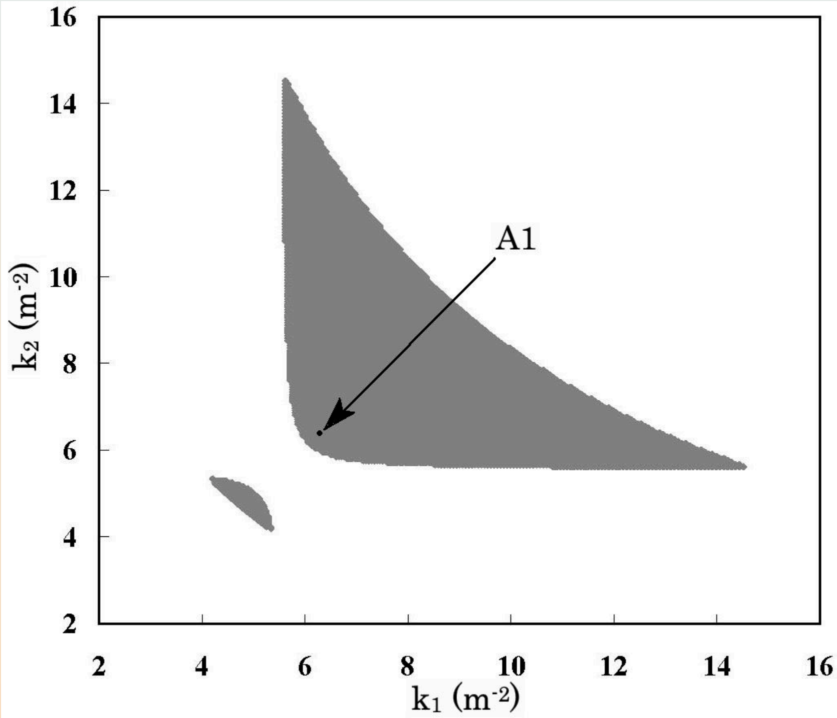
Thank you for your attention!!

ご静聴有難うございました。

Lattice Parameters of S-LSR

Magnetic Field superposed with Electric one, E(r)=k(const.)/r





B-function
Betatron tune =（1.49, 3.49）

Needs coupling cavity