イオン蓄積・冷却リングの可能性
－TARN, TARN-II, S-LSRの経験から－

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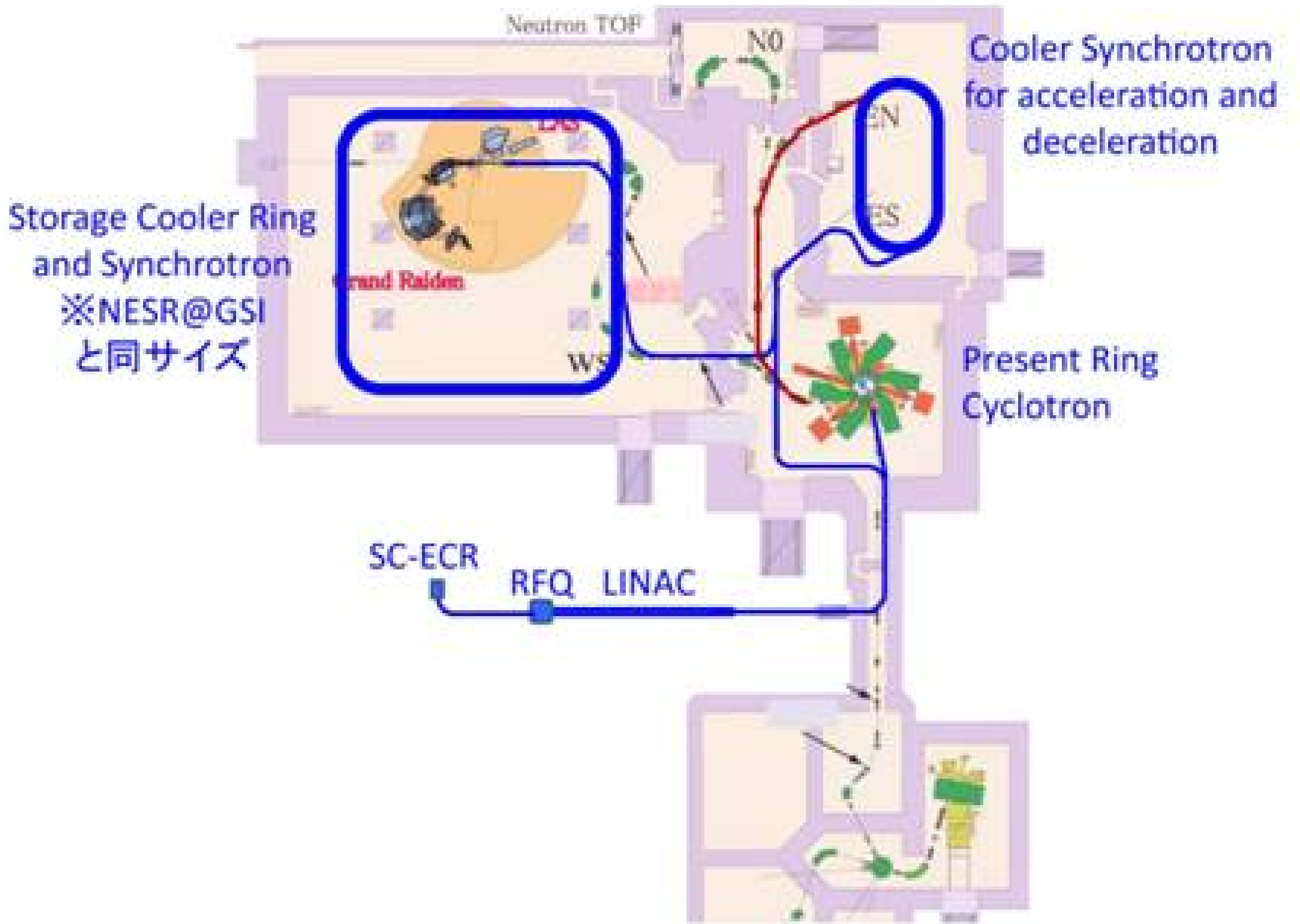
於

RCNP研究会「重イオン蓄積リングの物理」

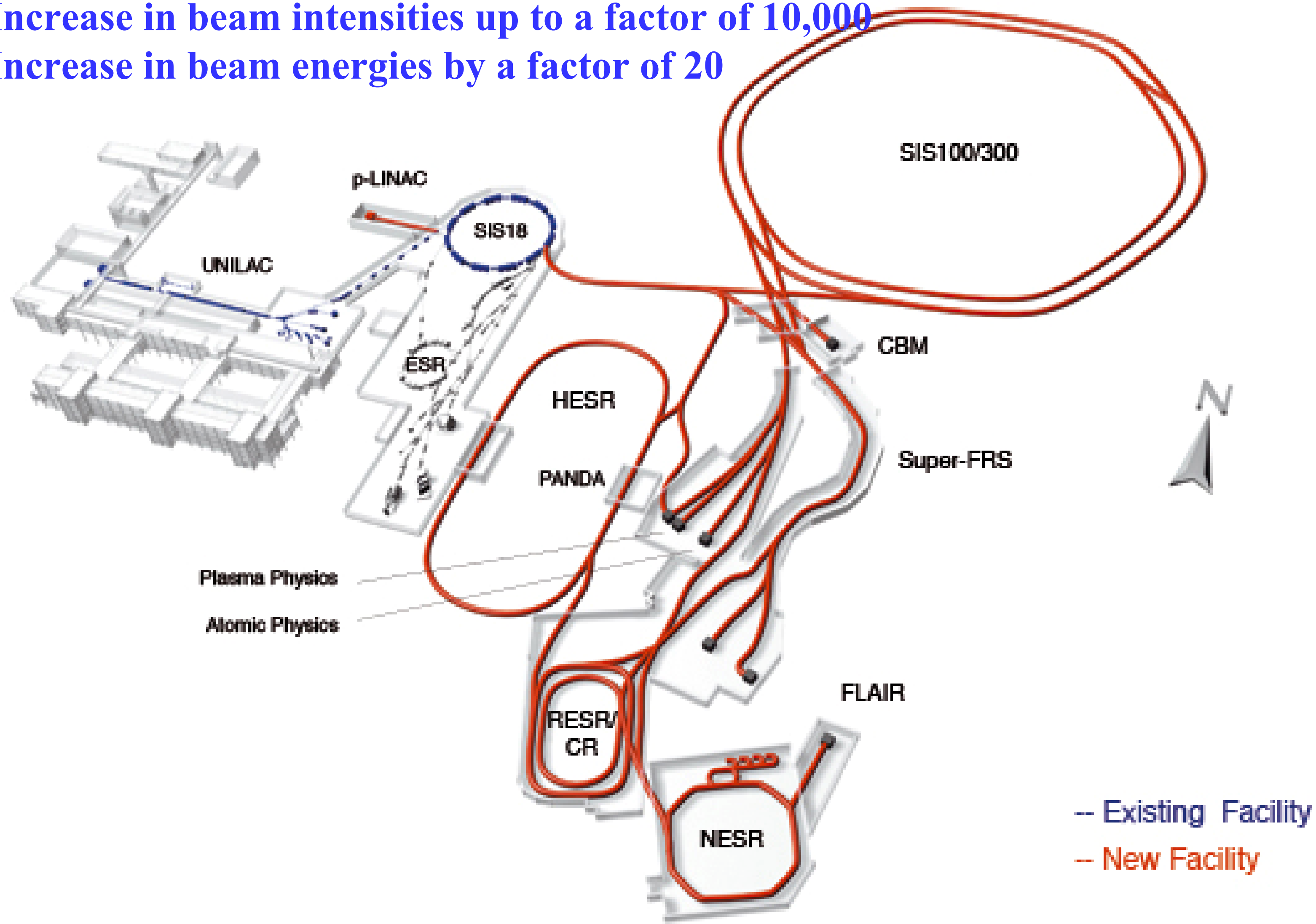
平成22年9月24～25日

New Accelerator Facility Plan at RCNP



GSI Present and Future

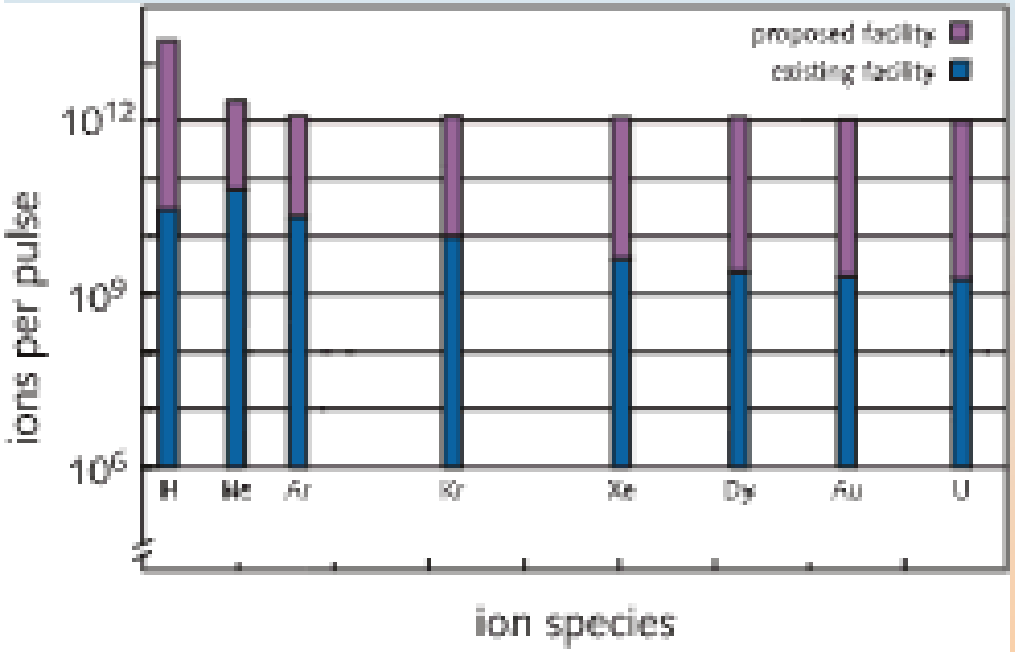
- Increase in beam intensities up to a factor of 10,000
- Increase in beam energies by a factor of 20

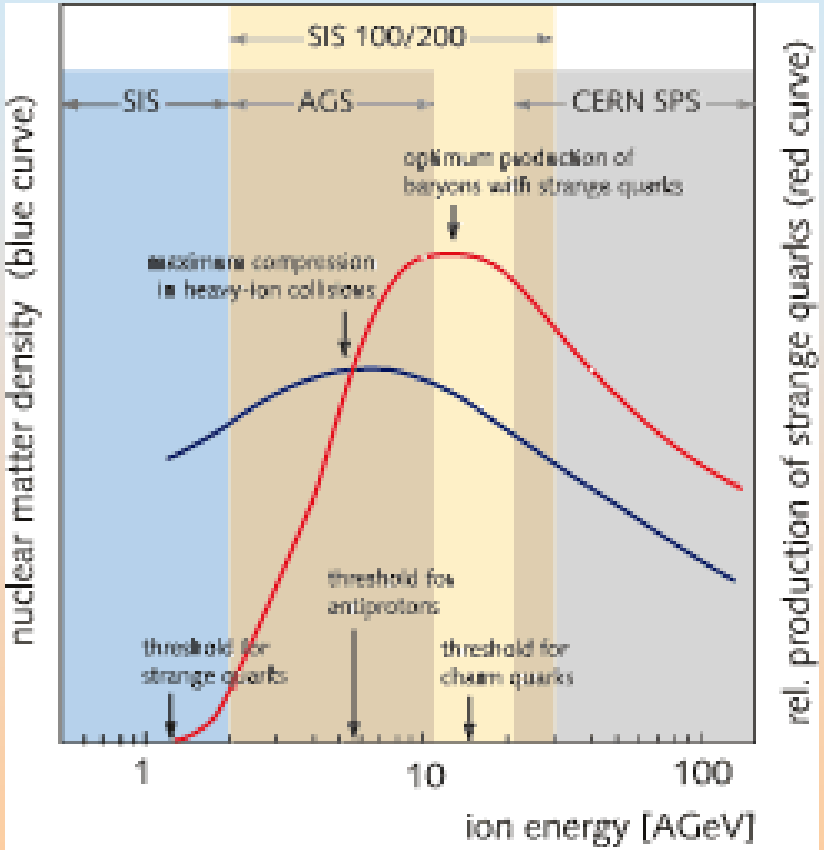


cf. Prof. A. Suzuki at LINAC2010 (12-17, September, 2010, Tsukuba, Japan)

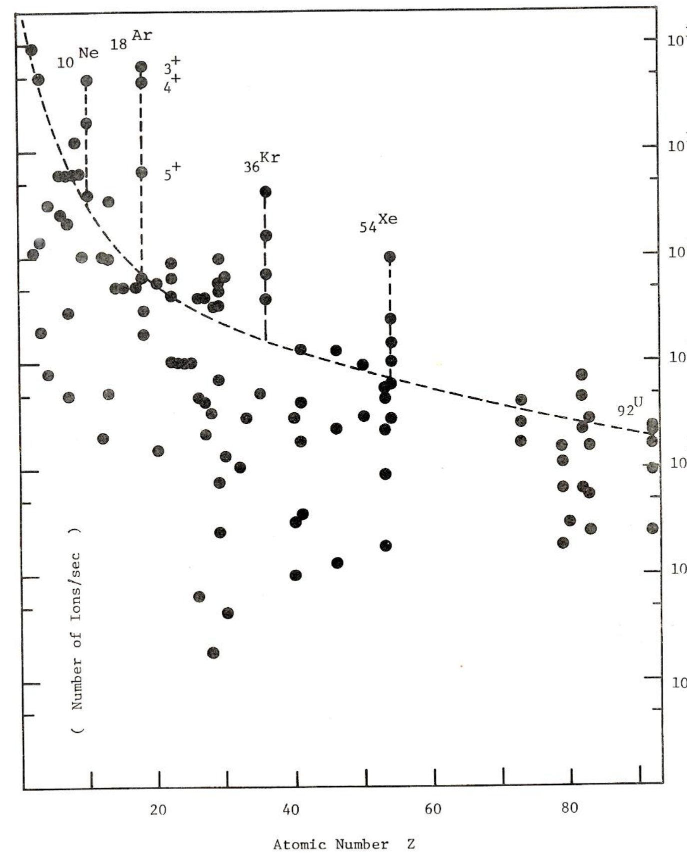
Energy x 1000, Intensity x 1000, Time Resolution x 1000

H.I. Beam Intensity (from GSI Home Page)

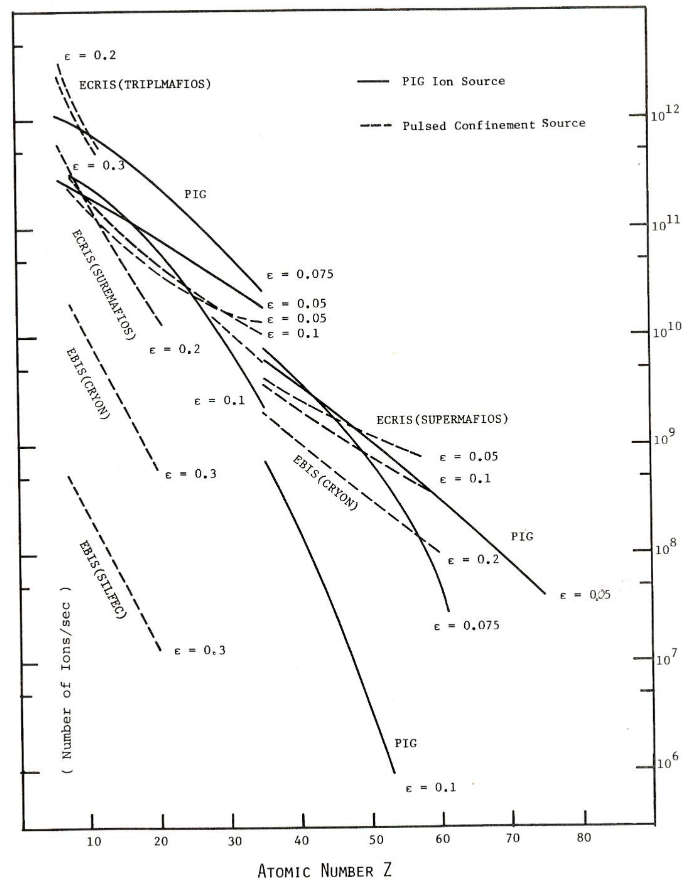




Without Amplification of Intensity at Injection Process to the Ring



Z-dependence of probable intensity with conventional ion sources



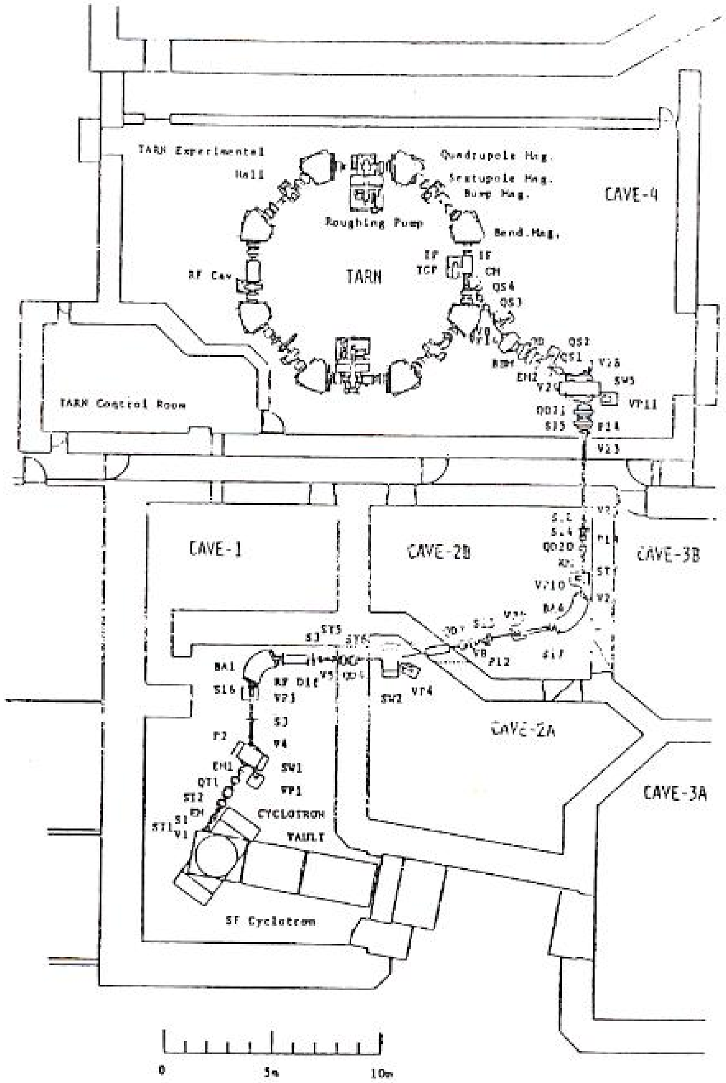
The output intensity of synchrotron.

— 73 —

From "NUMATRON" INS-NUMA-5

蓄積・冷却リングの役割

１．ビーム強度の増大
　　多重入射（横方向位相空間）
　　ＲＦスタッキング（縦方向位相空間）密度保存
　　Cooling Stacking
2.　ビーム特性の改善
　　ビーム冷却→運動量拡がり，ビームサイズの軽減
3．ビームの時間構造の改善
　　遅いビーム取り出し----Duty Factor改善
　　超短パルスビーム-----電子ビーム冷却



Layout of TARN and its transport line from the SF cyclotron.

Main Parameters of TARN

Max. Beam Energy9	8.55 MeV/u
Max. Magnetic Field	9.0 kG
Radius of Curvature	1.333 m
Average Radius	5.06 m
Useful Aperture	45 x 190 mm^2
Revolution Frequency	1.3 MHz
Betatron Tunes	(~2.25,~2.25)
Transition γ	1.894
Injection Method	Multi-turn
Momentum Spread of Stacked Beam	2.5 %
Rep. Rate of RF Stacking	30 Hz
Vacuum Pressure	~1 x 10 $^{-10}$ Torr

Taken from Proc. of 1984 INS Int. Symp. on Heavy Ion Accelerators and Their Applications to Inertial Fusion

TARN-I

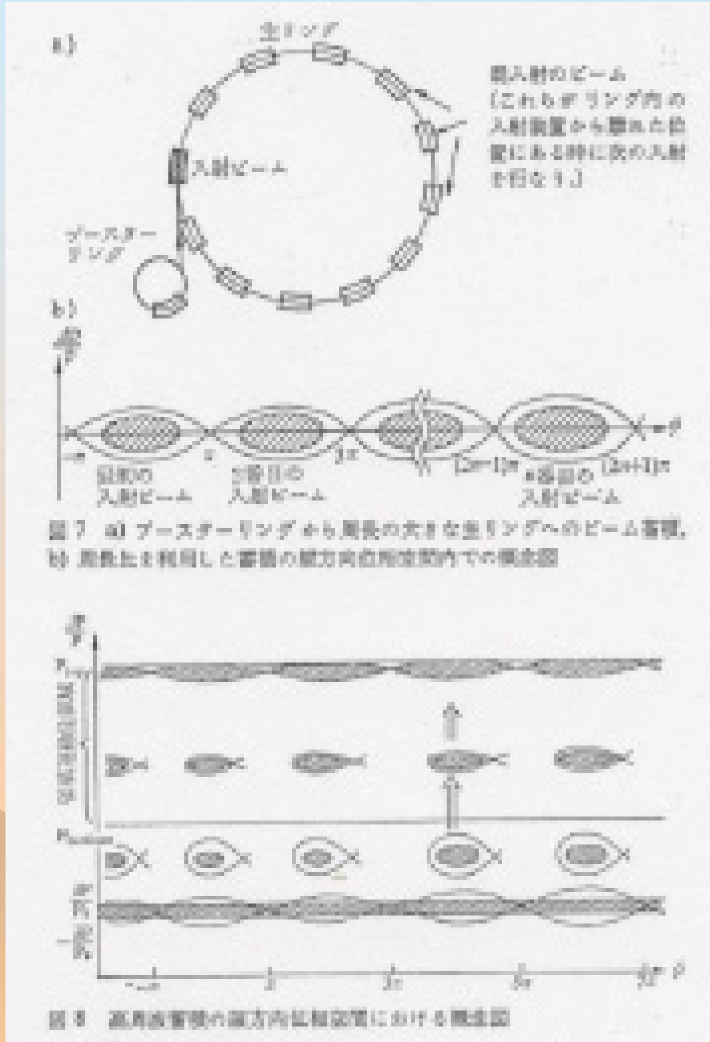
1. **Combination of Multi-turn Injection and RF stacking → Totally ~300 times peak intensity increase**

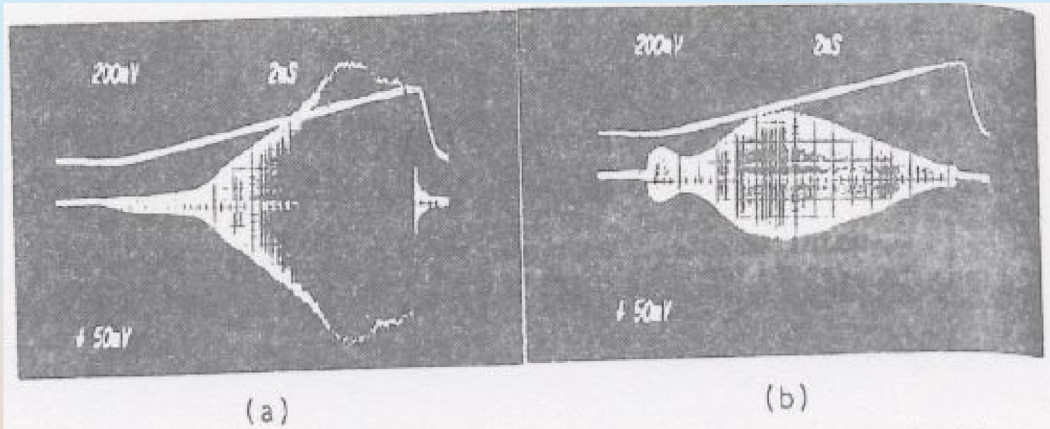
   → Momentum Spread of 2.5 % cannot match with further acceleration with capture into a separatrix→ $qeV = (\frac{\Delta E_m}{\beta})^2 \pi h |\tilde{\eta}| / [(\pi - 2\varphi_s)\sin\varphi_s - 2\cos\varphi_s]$

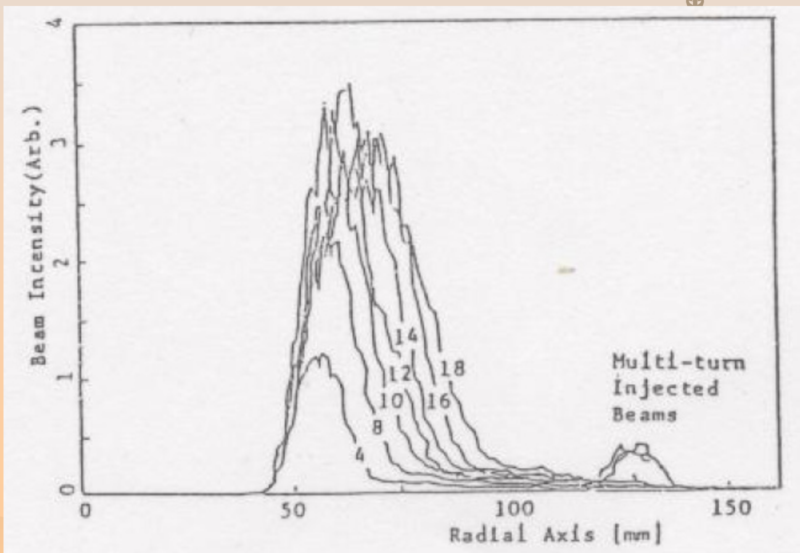
   Large energy spread needs phase space displacement→needs time for acceleration, poor acceleration efficiency

2. **Stochastic Cooling with Notch Filter (longitudinal phase space)**

Phase Displacement Acceleration







Stochastic Momentum Cooling at TARN

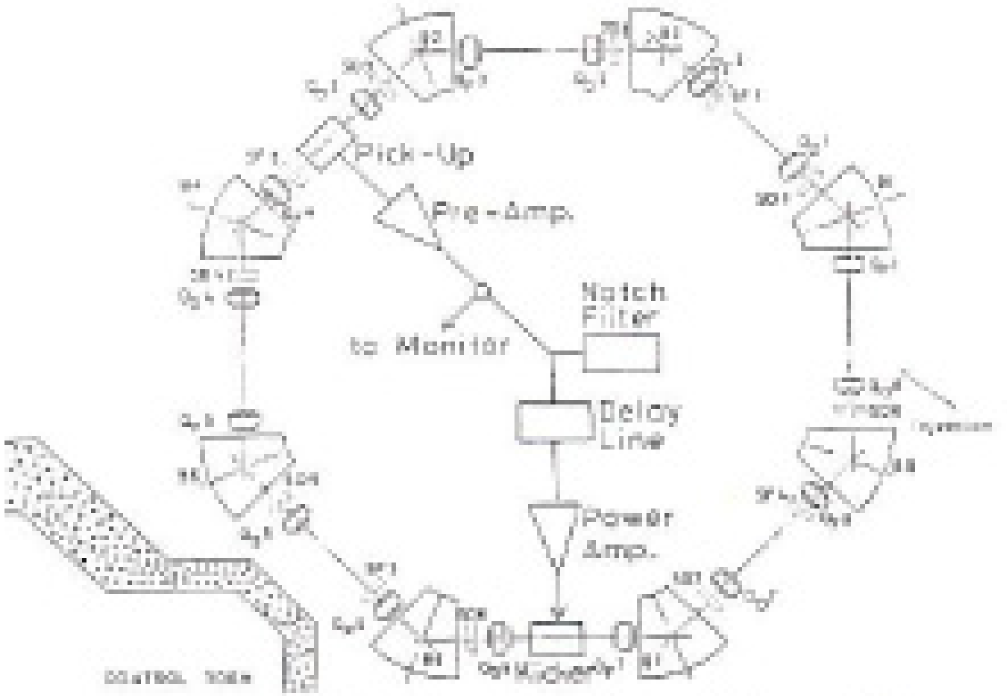
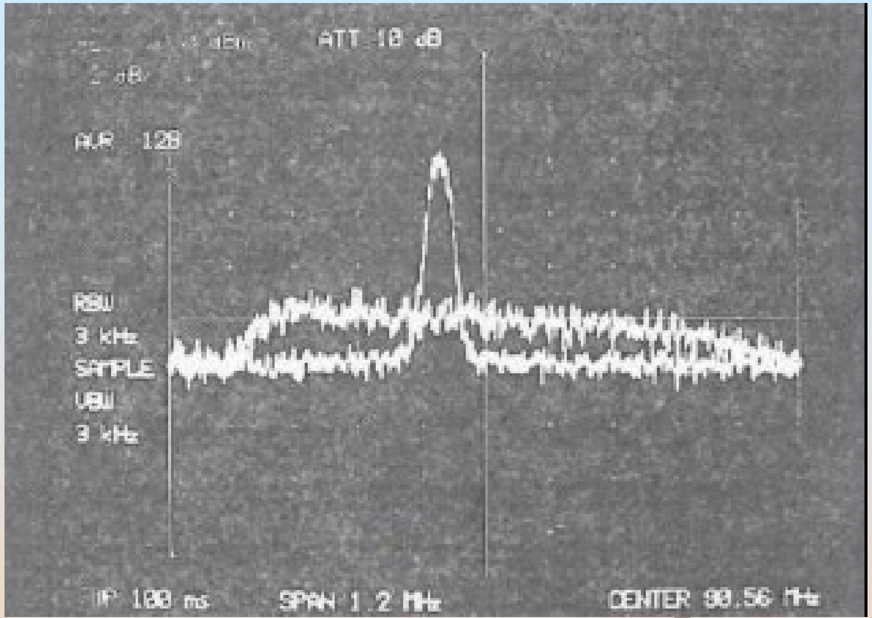


Fig. 13 Layout of the stochastic cooling system for TARN.



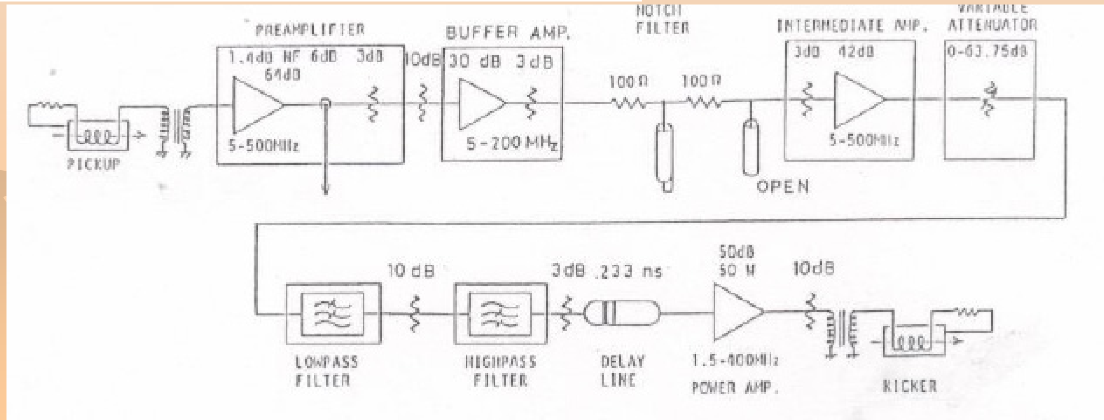
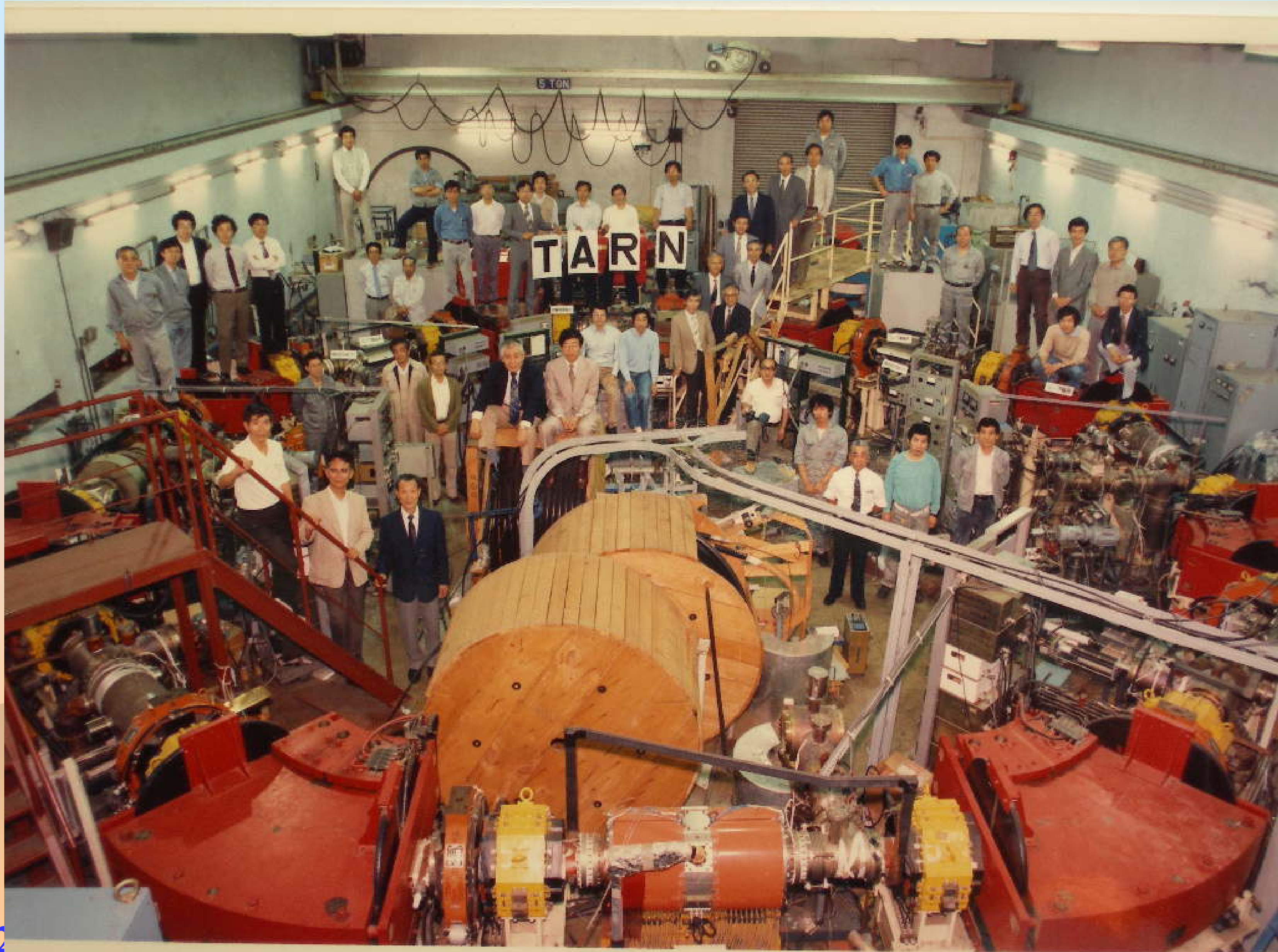
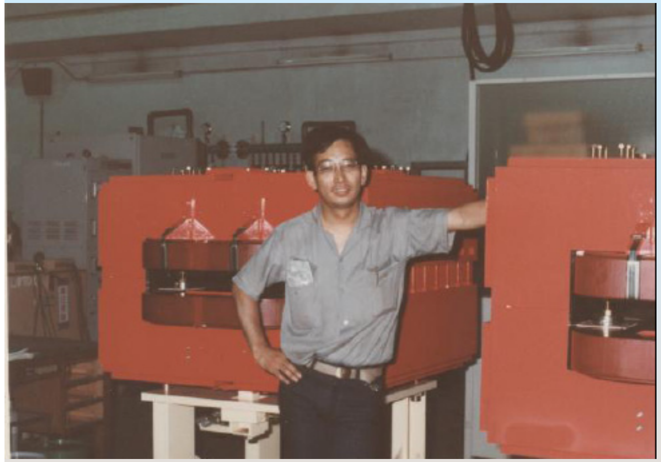


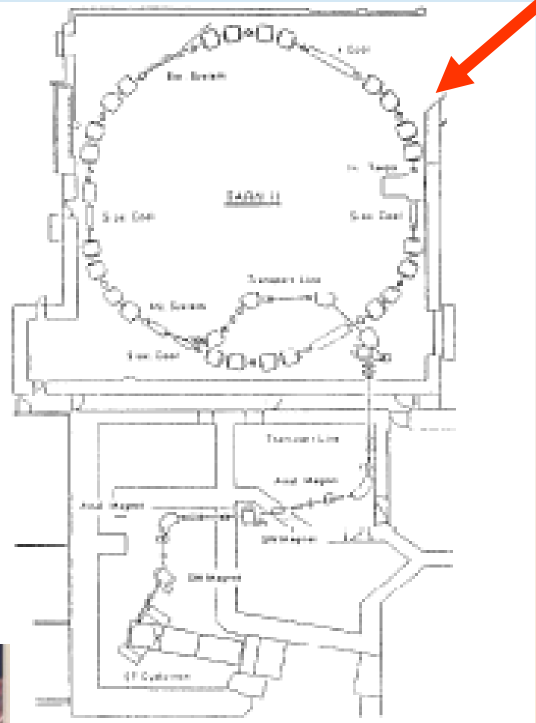
Fig. 14 Block diagram of the stochastic momentum cooling system at TARN.

TARN to be Upgraded to TARN -II

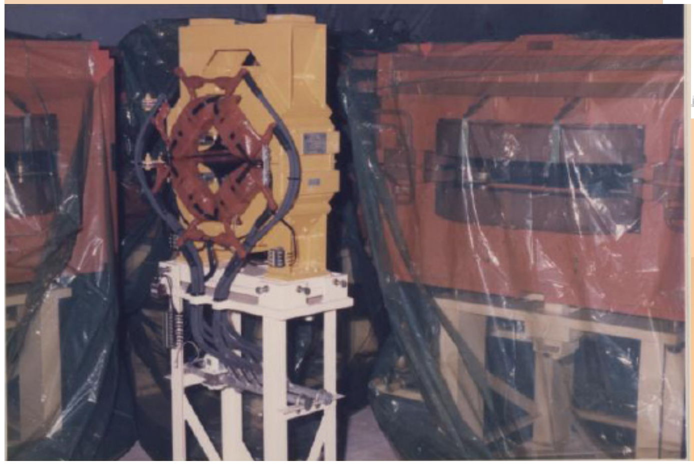


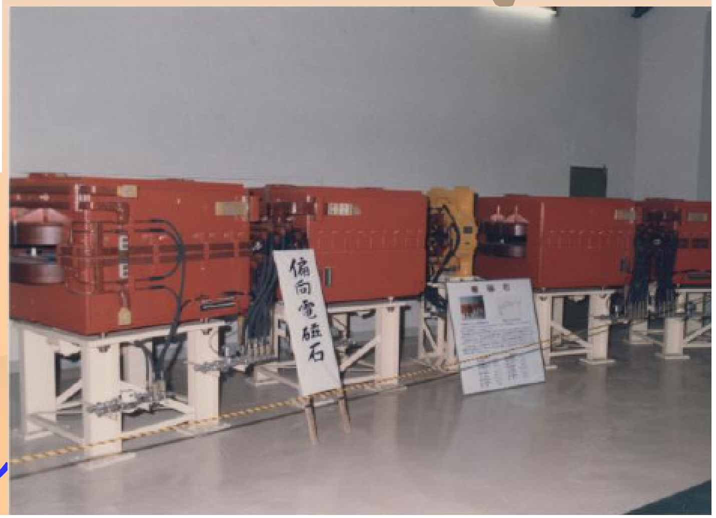
Construction of TARN-II





g. 1 Layout of TARN II and its transport line.





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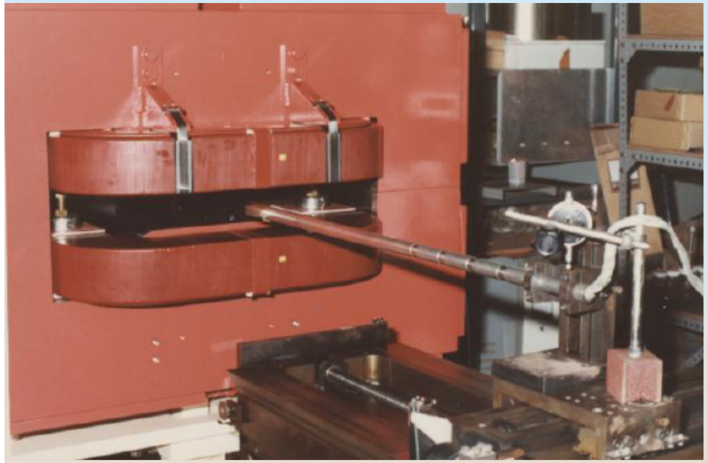
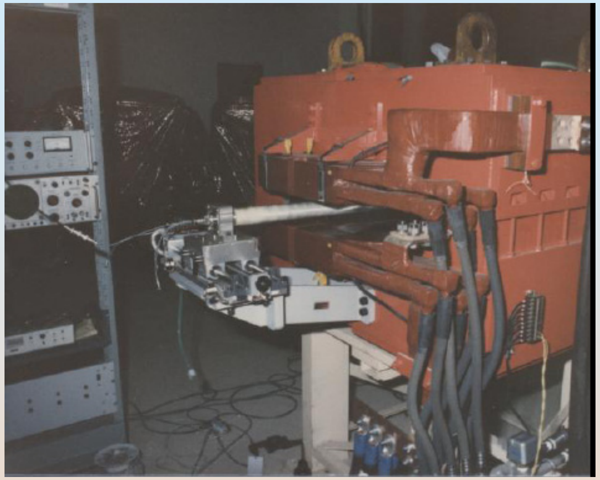
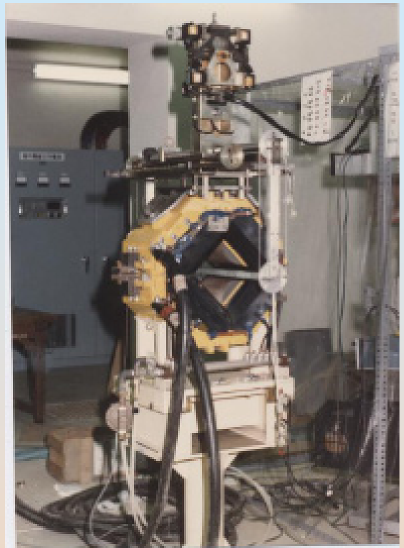
Evaluation of Magnets







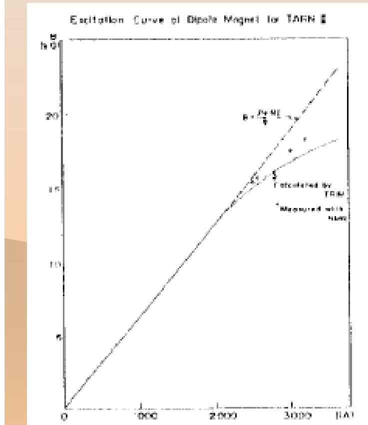


Fig. 3 Excitation characteristics of the dipole magnet for TARN II.

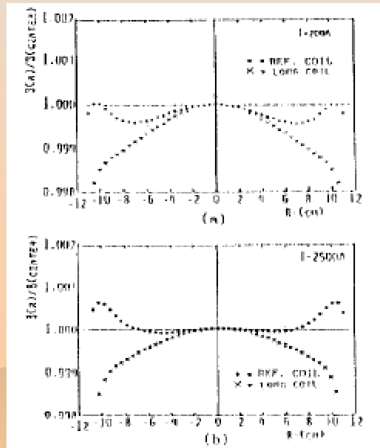
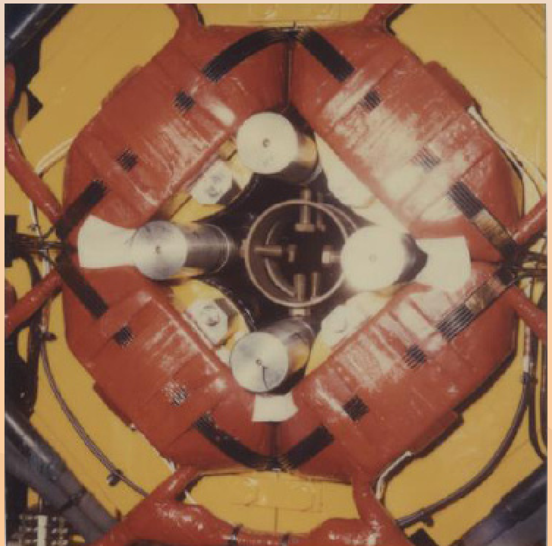
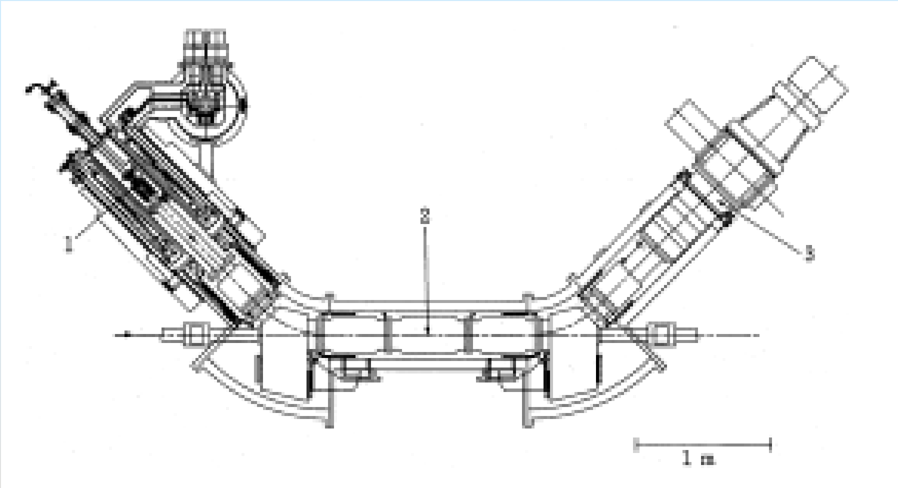
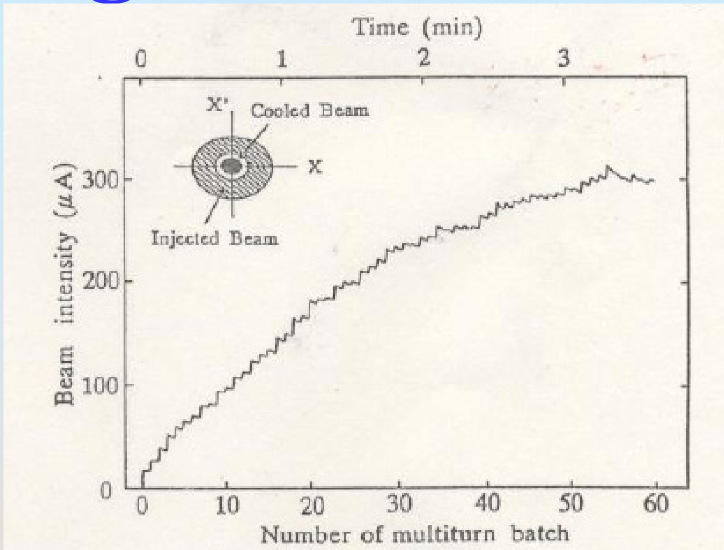


Fig. 4 Radial field distributions of dipole magnet, (a)200 A and (b)2500 A.

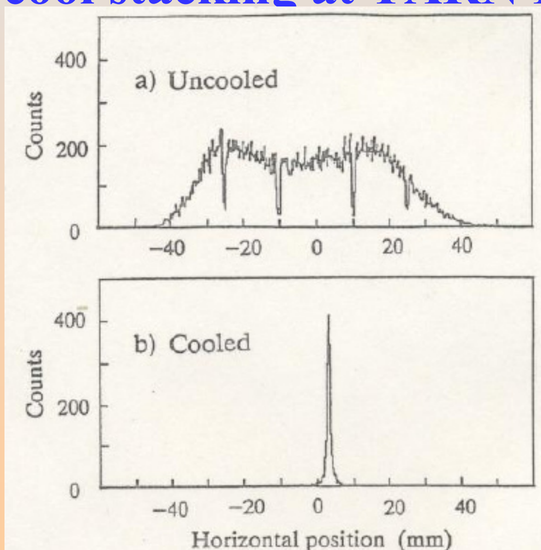


Electron Beam Cooling at TARN II





E-cool stacking at TARN II



From T. Tanabe et al., N.I.M.A441(2000) pp326-338 and Proc. 5th Japan-China Joint Symp. (1993) Osaka, pp16-20.

High Resolution Experiment

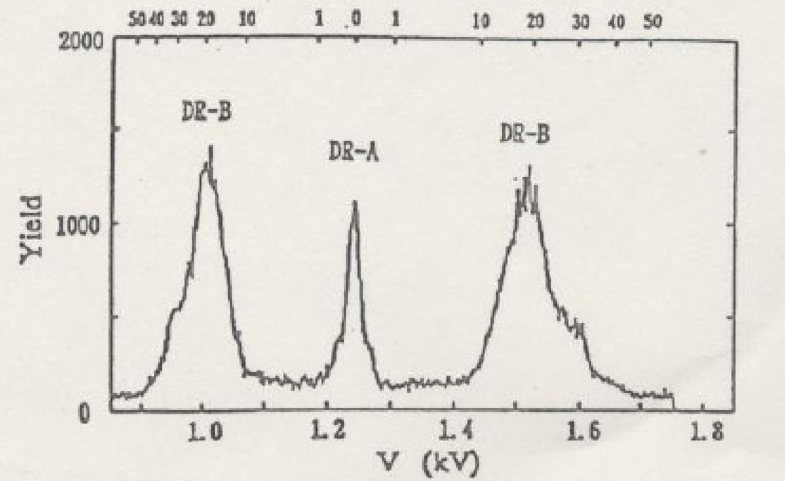


Fig. 9. Yield of neutral He+H atoms formed in the dissociative recombination $HeH^+ + e \rightarrow He + H$ as a function of electron acceleration voltage. The c.m. energy scale is also shown. The time window is 0.92-1.47 s and the electron current is 0.2 A

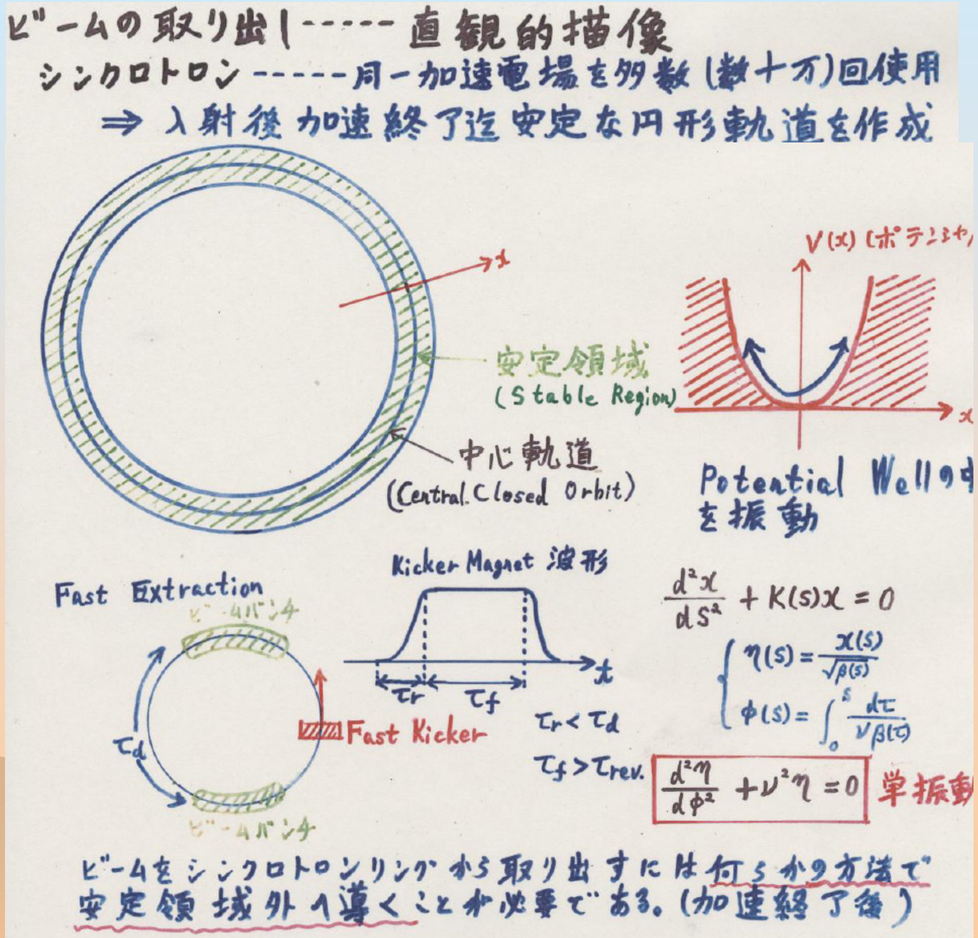
From T. Tanabe et al., Proc. 5th Japan-China Joint Symp. (1993) Osaka, pp16-20.

Variation of Revolution Frequency

$$\frac{\Delta f}{f} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}{}^2}\right)\frac{\Delta p}{p} + \frac{\partial f}{\partial m}\frac{\Delta m}{m}$$

- **Electron beam cooling**
  →Δp/p tends 0
- **Precise mass analysis becomes possible**

Beam Extraction



Fast Extraction

リング内に設置された非常に立ち上りの速い(数10 nsec~ a few $\times 10^{-8}$ sec)パルス磁場によりリング中を周回している全てのビームを一回転の間に安定領域から取り出す。
~1 μsec

⇒ビームのピーク強度高い ~10^{16} 個/秒 ……粒子の個別計測困難

Slow Extraction

リング内の不整磁場等による共鳴現象(Resonance)を利用し、振幅の増大を図り、一定振幅以上のビームのみを取り出す。

$$\frac{d^2x}{ds^2} + K(s)x = f(t,s)$$

強制振動

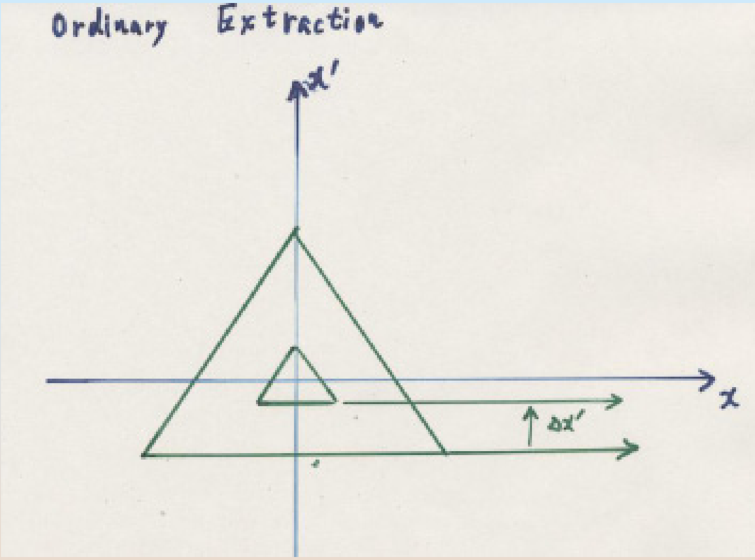
全てのビームの取り出し、ベータトロン振動数を徐々に ν_{res} に近づける。(~msec order)

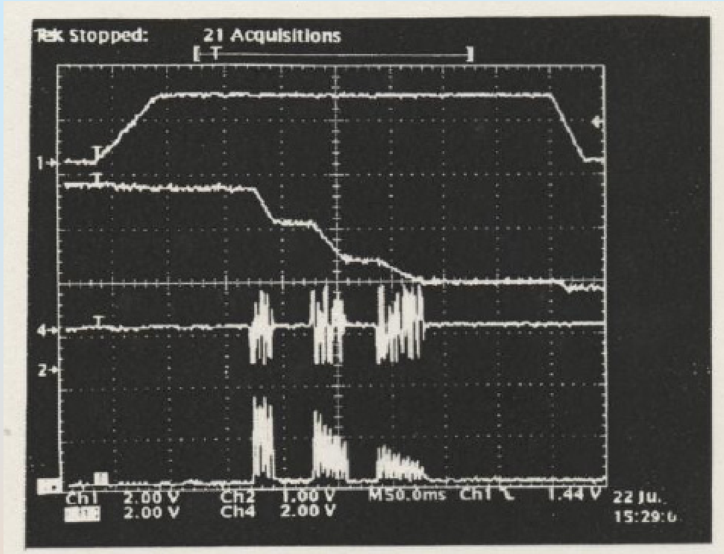
RF KO による取り出し

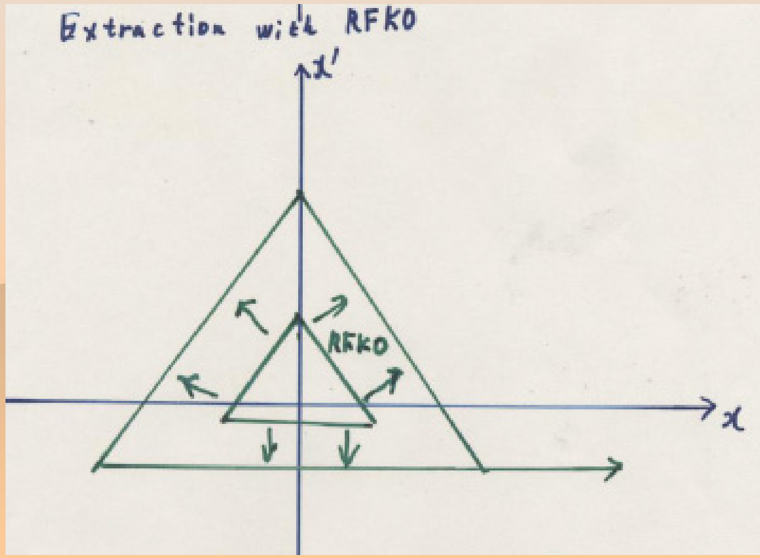
ベータトロン振動に共鳴する横方向RF電場による強制振動を惹起する。

→ RFの ON/OFF は μsec order response

Slow Beam Extraction by RFKO







Merit

- Fast Beam On/OFF <μsec.
- Extracted Beam Direction does not change in time
- very long beam spill time is attainable

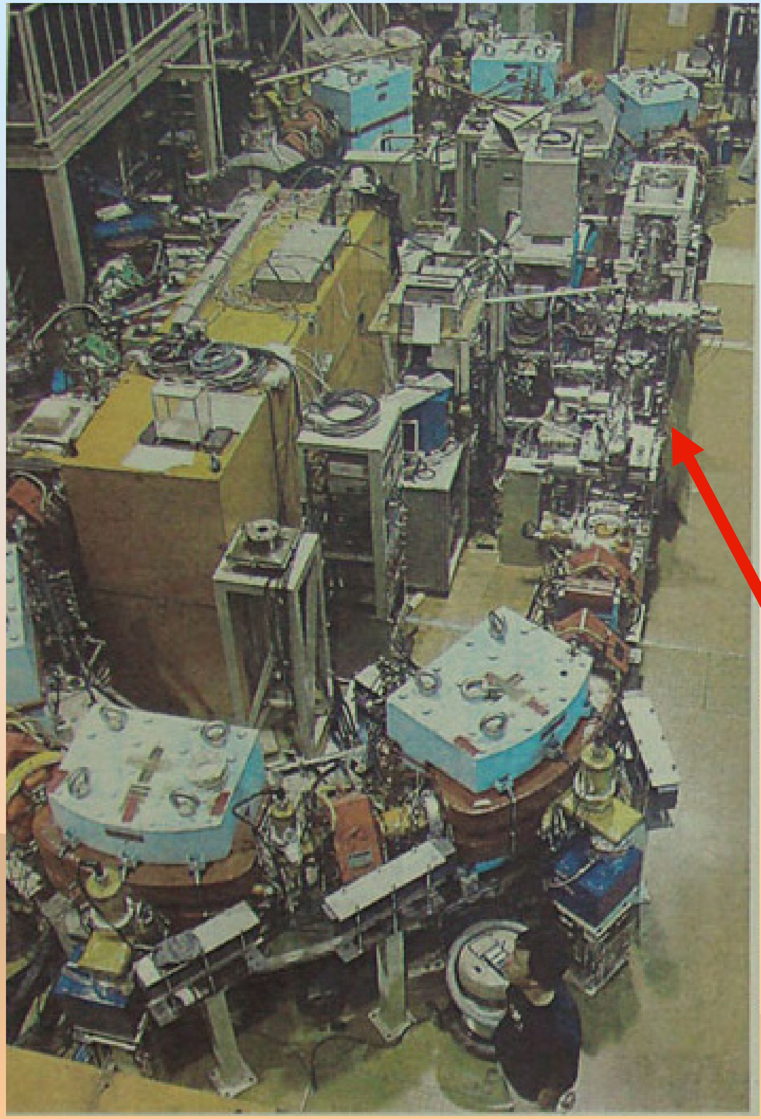
Demerit

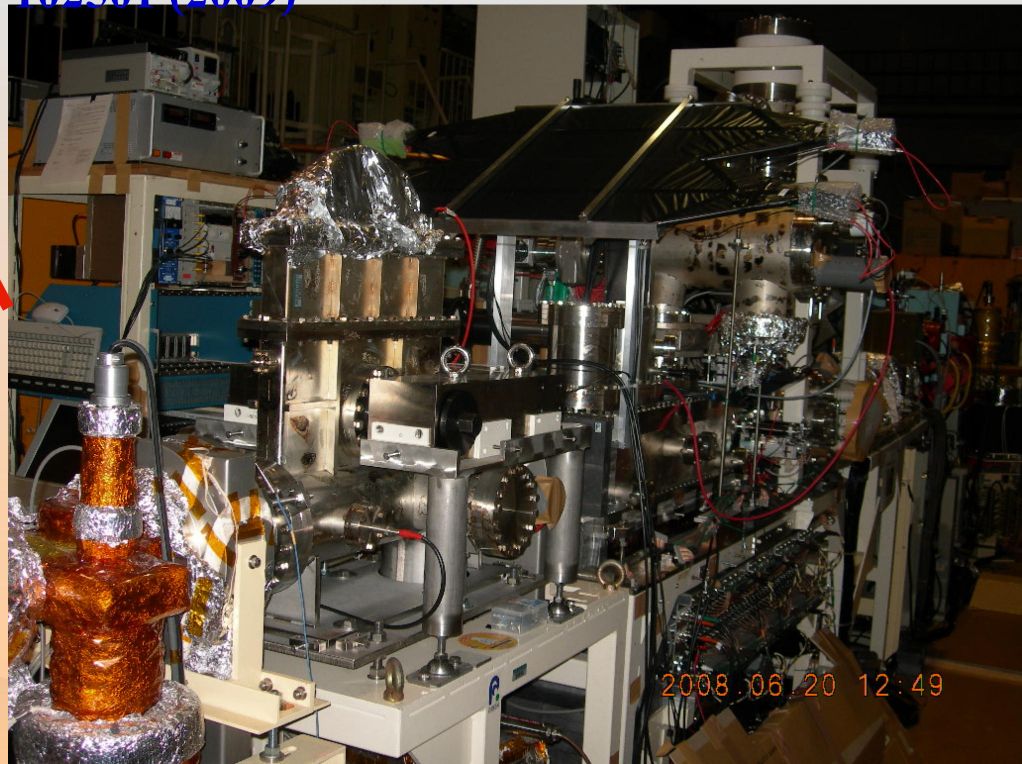
- Time structure due to RF Frequency for RFKO

SCRIT Installed into S-LSR

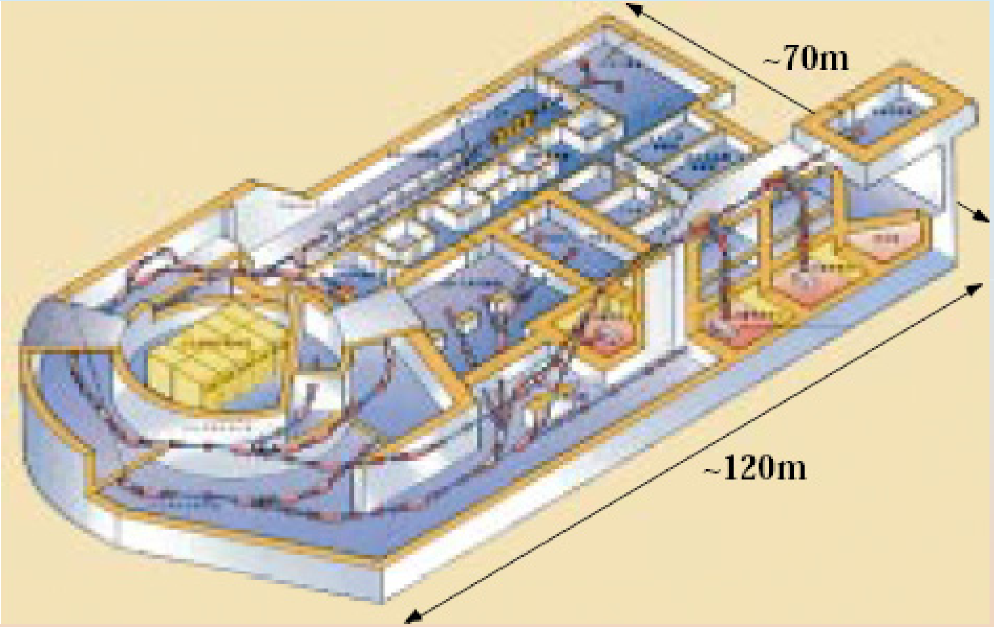
SCRIT(self-confining radio active isotope ion target)
An "ion trapping" phenomenon in the electron storage ring was successfully utilized for the first time to form the target for electron scattering.

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





Development of Compact Cancer Therapy Machine with Use of Laser Ion Source



HIMAC at NIRS in Chiba

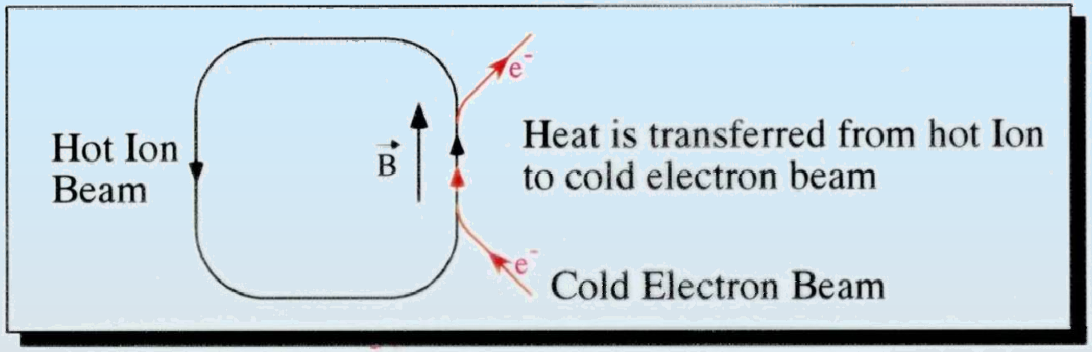
Pulse Synchrotron (KEK)

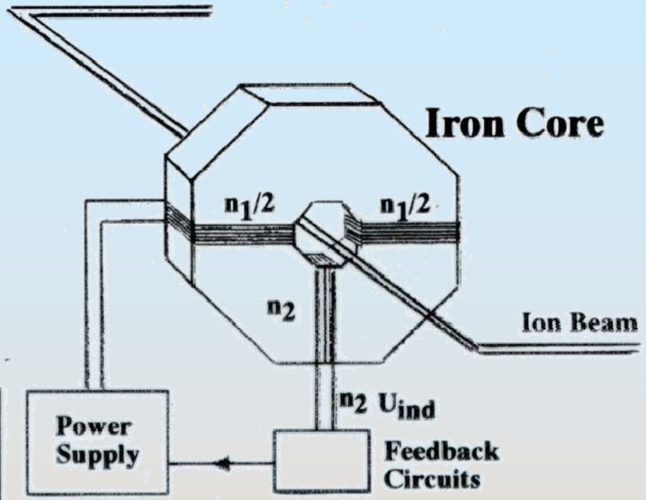
Electron Beam Cooling (Kyoto Univ.)

Laser Ion Source (JAERI, Kyoto Univ.)

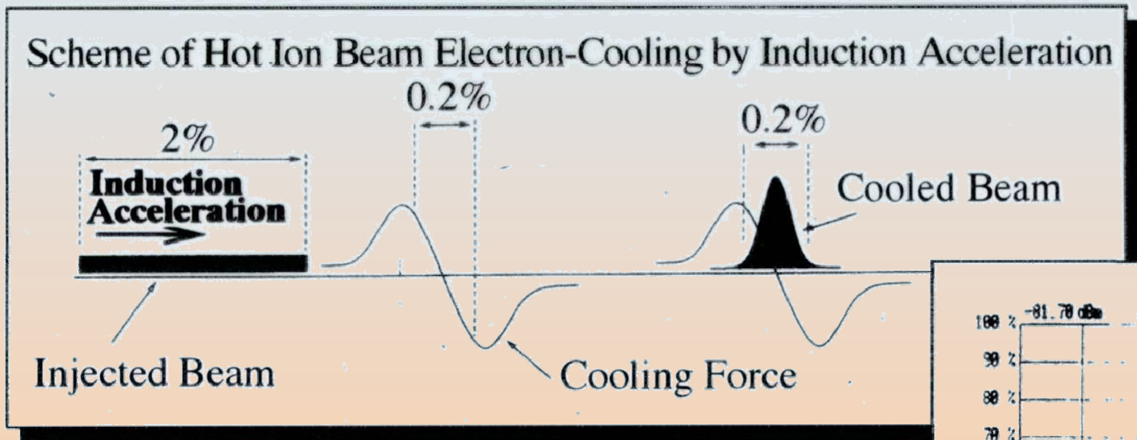
Phase Rotation (Kyoto Univ.)

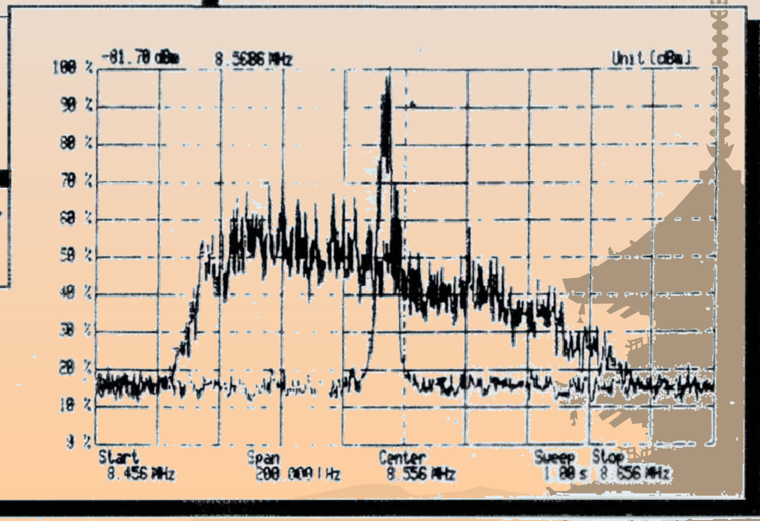
Electron Beam Cooling Scheme of Hot Ion Beam





Principle of Induction Acceleration

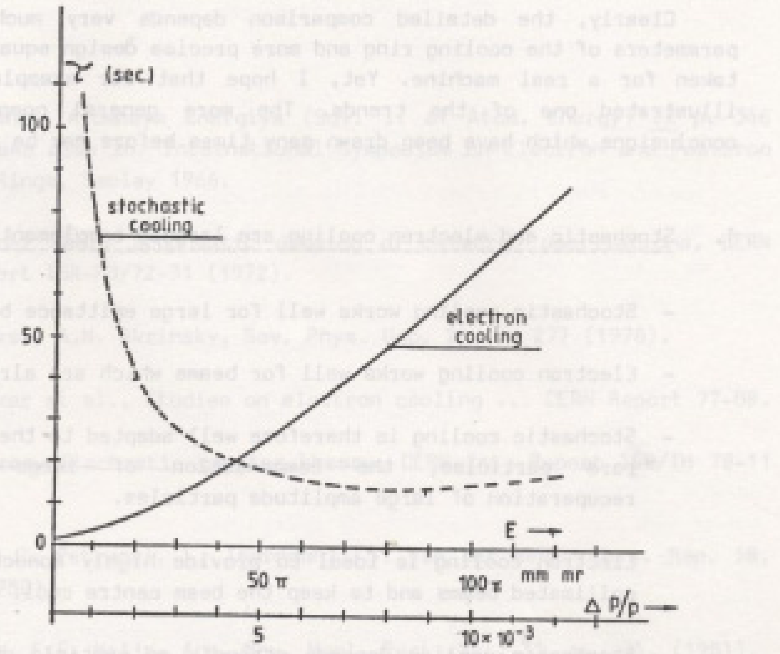




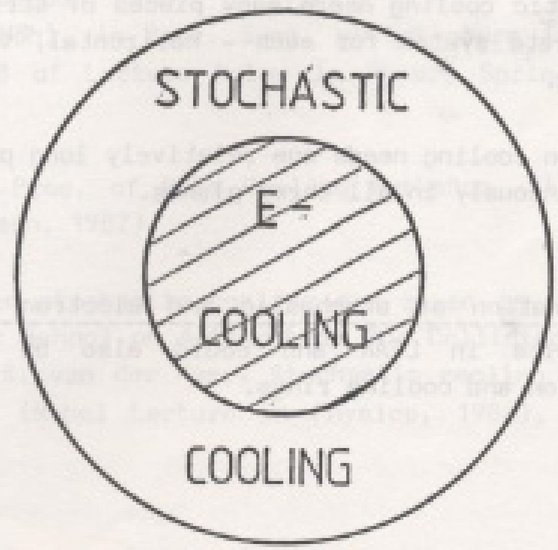
Example of the Momentum Spread before
and after Electron Beam Cooling
(obtained at TSR, E. Jaeschke and D. Krämer
Phys. BI.45(1985) pp.86-87)

By D. Möhl., Proc. of ECOOL84, Kahlsruhe, Germany (1984)

Comparison of Beam Cooling Methods



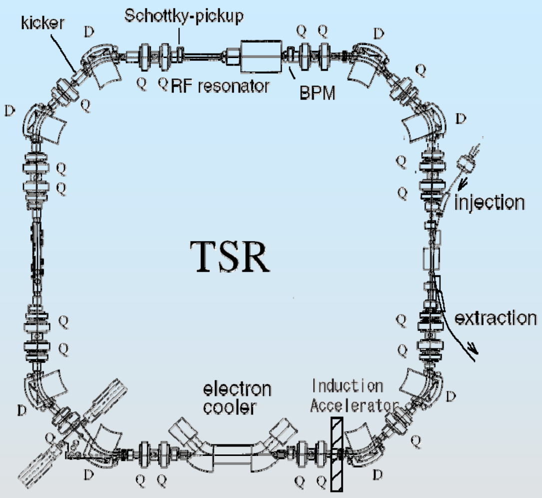
Stochastic and electron cooling time as a function of beam emittance.



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.

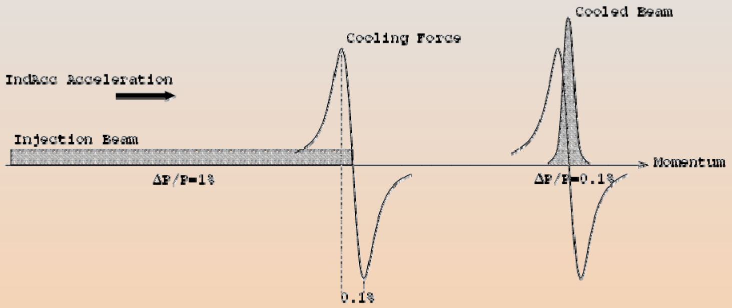
Electron Cooling of Hot Ion Beam at TSR

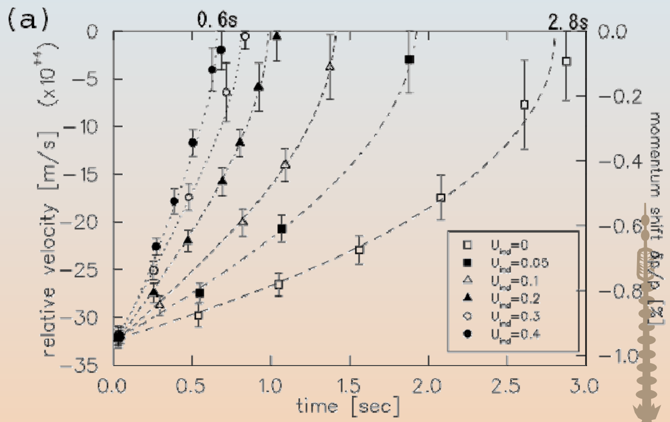
by H. Fadil



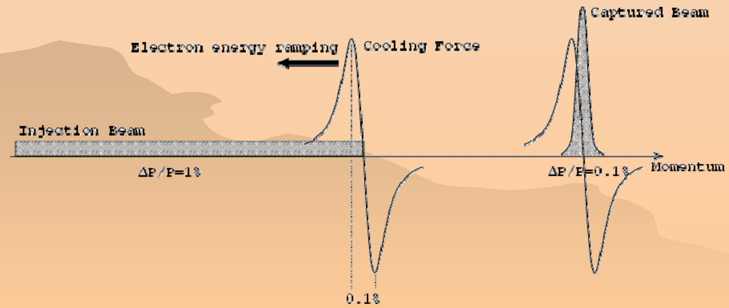
TSR Experiment parameters	
Ion species	C^{6+} 73.3 [MeV]
Electron density	2.4×10^{7} [cm^{-3}]
cooler length	1.2 [m]
Magnetic field	300 [G]
Induction voltage	0 ~ 0.4 [V]

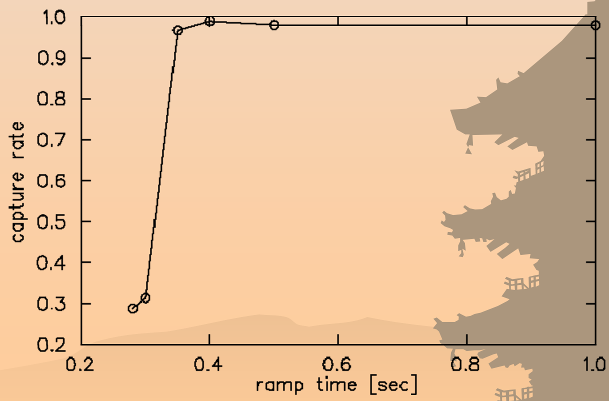
Ion beam energy sweeping scheme





Electron beam energy sweeping scheme



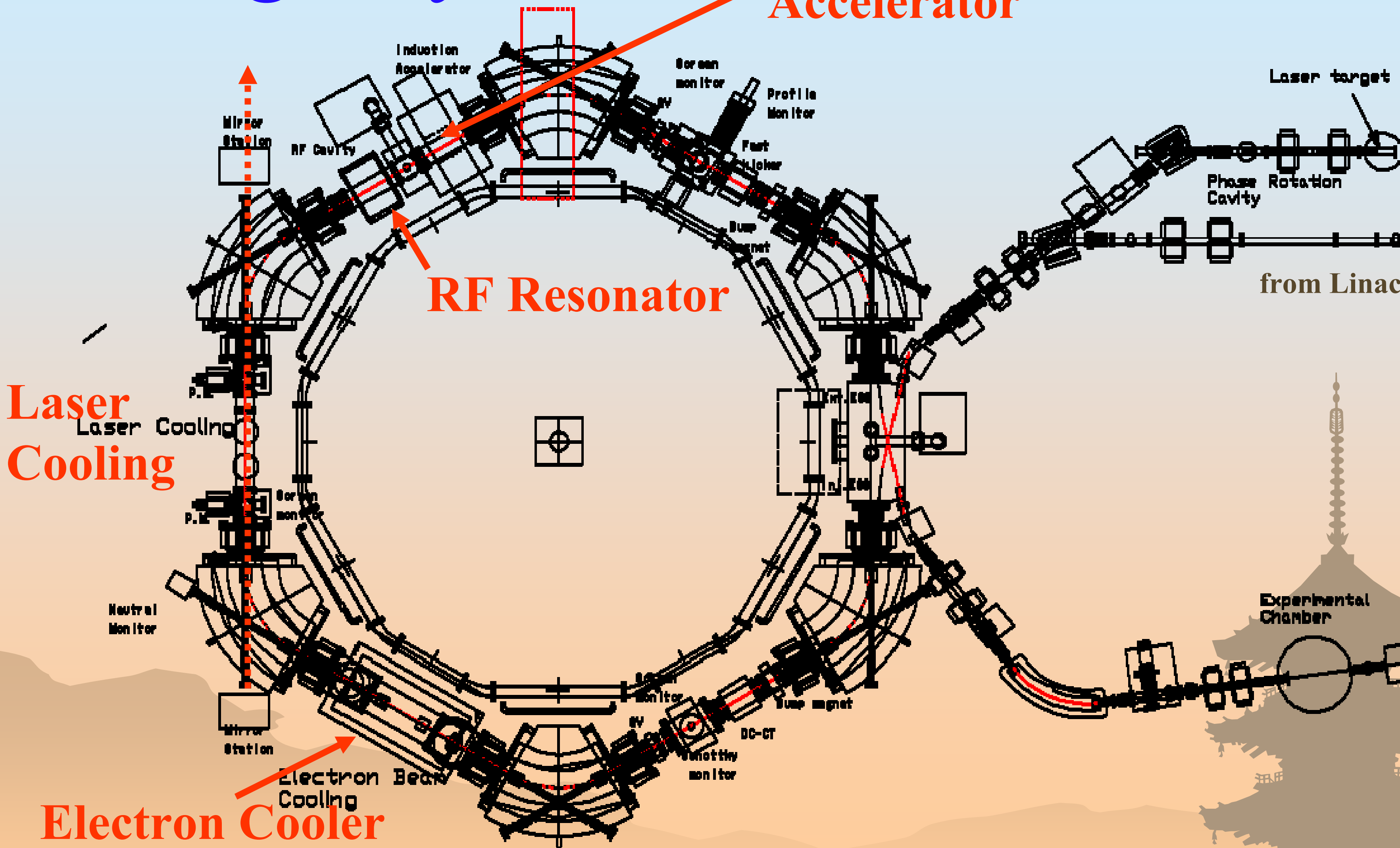


Main Parameters of S-LSR

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

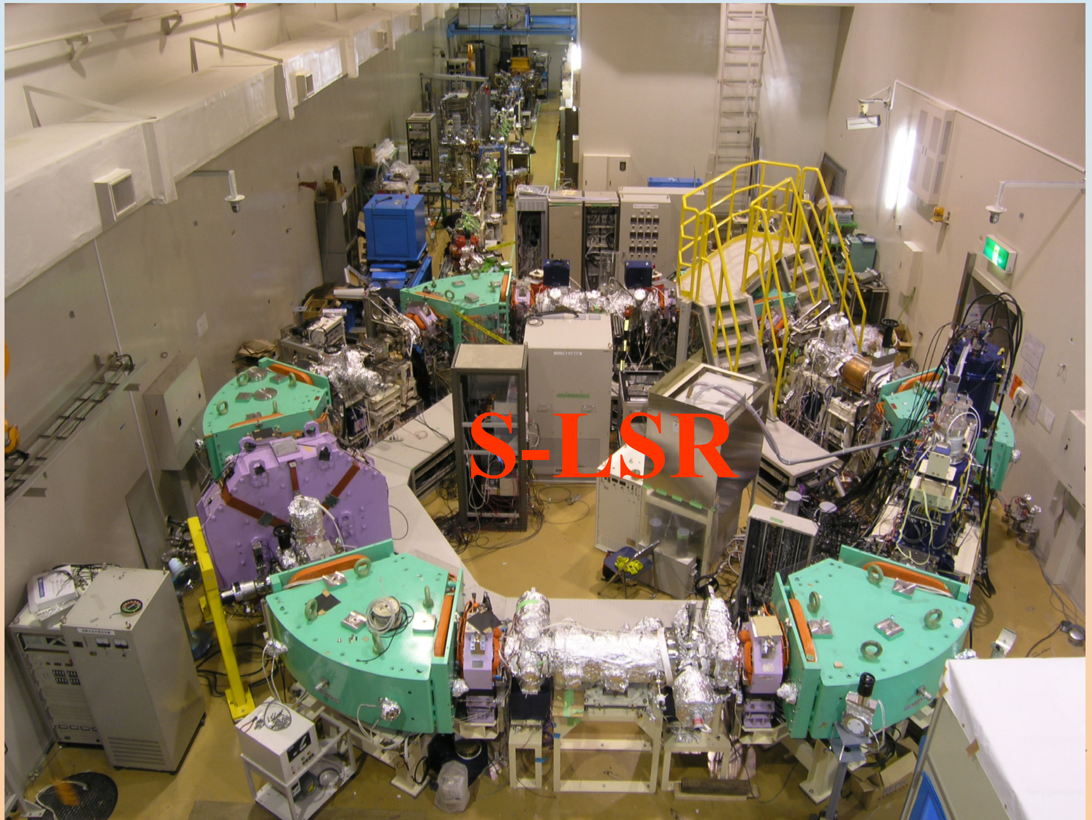
Ring Layout

Induction Accelerator

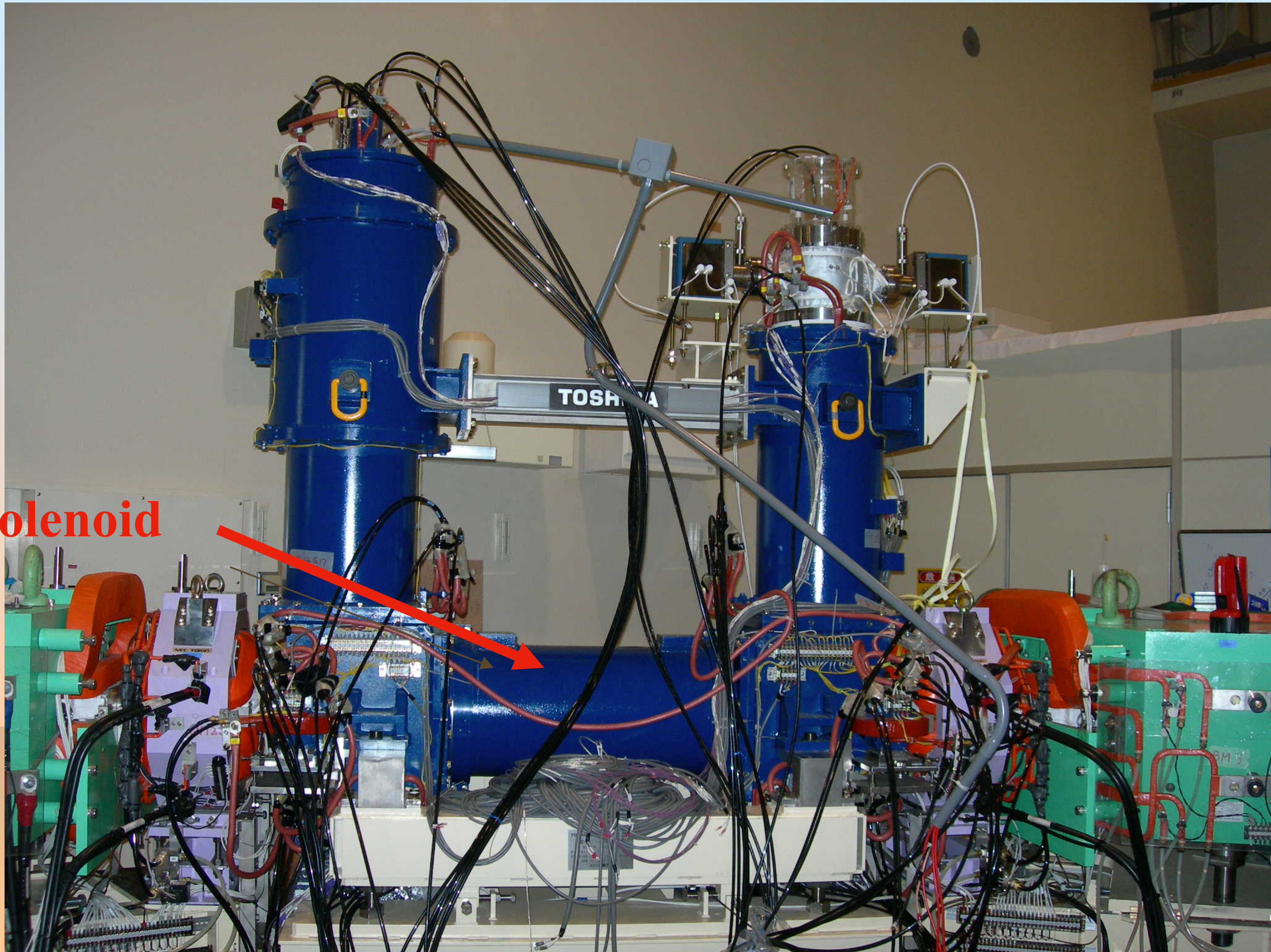


- Compact Cooler Ring S-LSR
  - Circumference 22.56m
  - Straight Section Length 1.86m
- Two e-cooling modes
  - Protons 7MeV (Ee=3.8keV)
  - $^{12}C^{6+}$ 2MeV/u (Ee=1.1keV)
- Laser cooling
  - $^{24}Mg^{+}$ 40 keV (λ=282 nm)

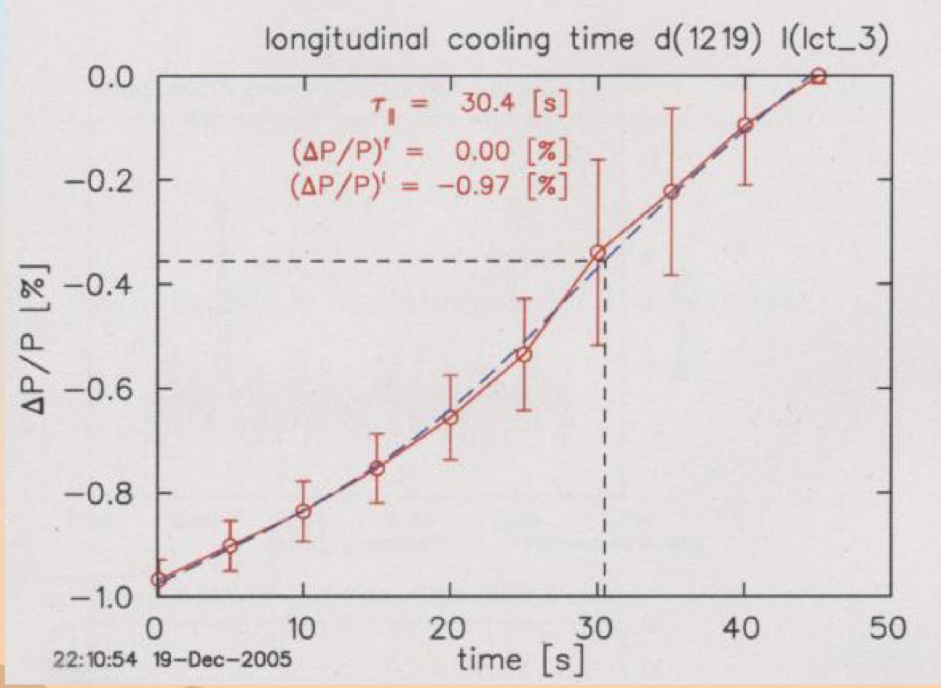
In operation since October, 2005

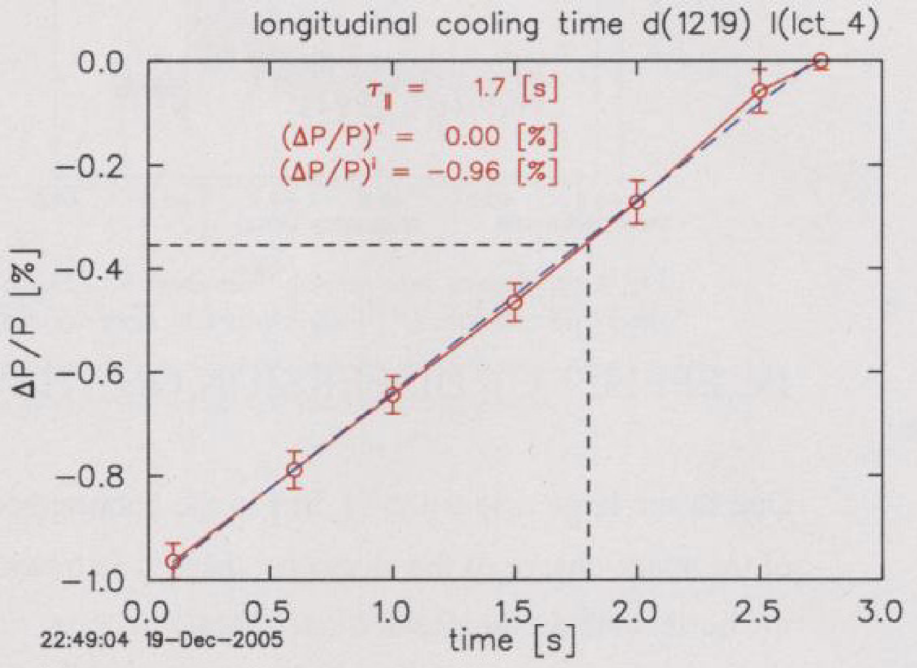


Electron Cooler installed in S-LSR



Electron Cooling of Hot Ion Beam





ESR at GSI, by M. Steck

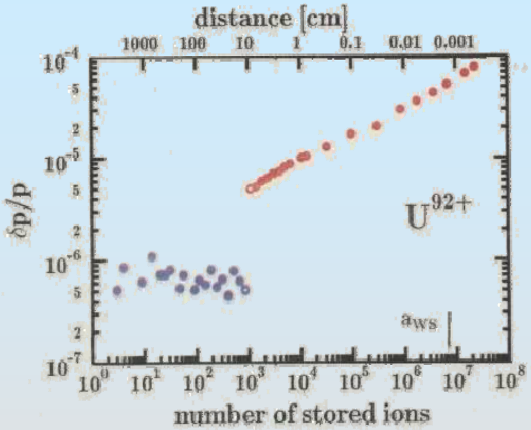


Figure 2. Experimental momentum spreads from Schottky signals *vs.* number of stored ions in the ESR for electron cooled U^{92+} ions at 240 MeV/u. a_{WS} indicates the Wigner-Seitz radius of eq.(3). (after ref. [9])

CRYRING at Stockholm, by H. Danared

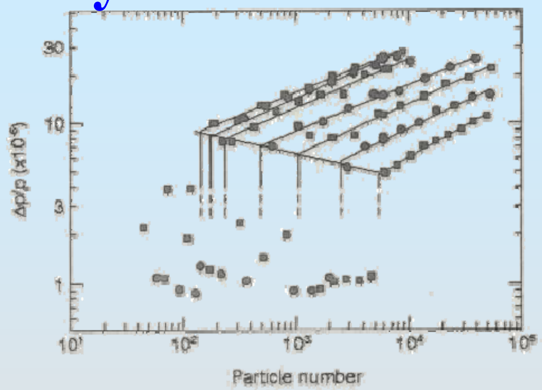


Fig. 5: Relative momentum spread as a function of particle number for the lowest seven electron densities represented in Fig. 2. The density increases from the upper left to the lower right. For each density, a line is fitted to the data points. A line is also drawn through the points corresponding to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

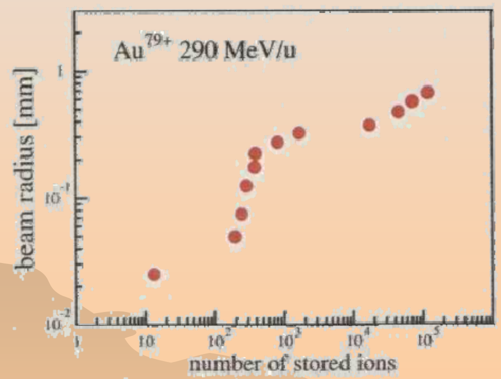


Figure 3. Beam radius measured with a beam scraper *vs.* number of stored ions in the ESR for electron cooled Au^{79+} ions at 290 MeV/u (from ref. [10]).

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

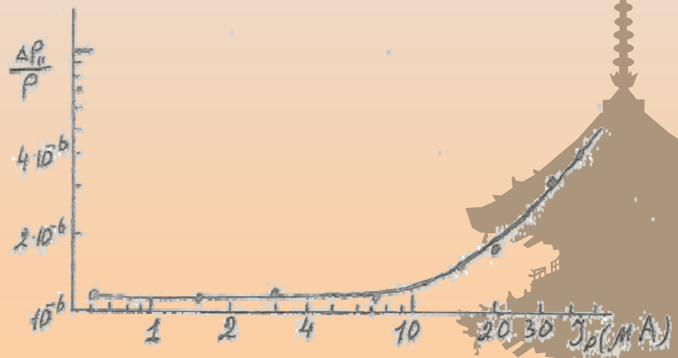
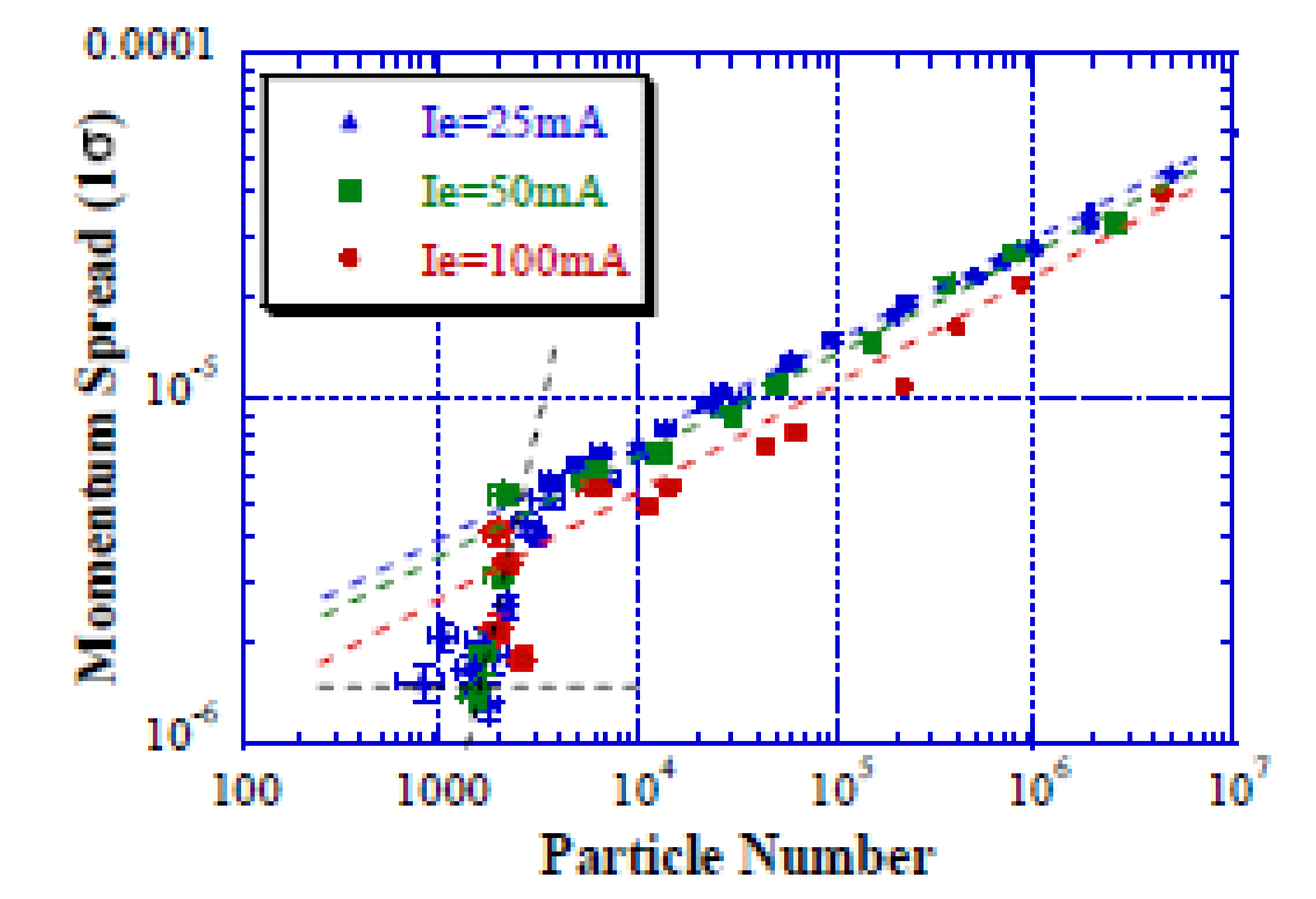


Fig. 6. The momentum spread of proton beam versus current J_p.

Phase Transition to 1D Ordered State



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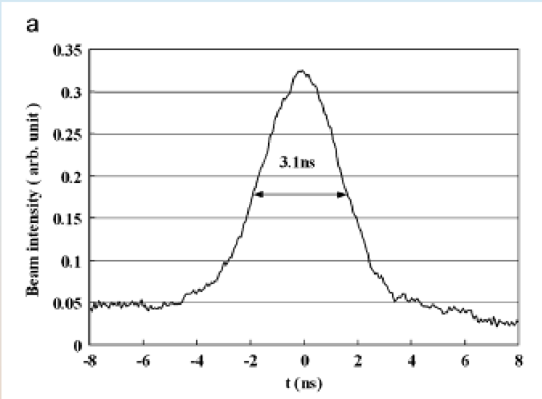
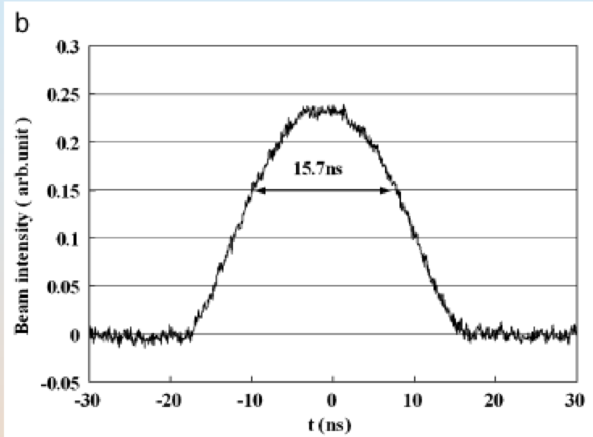
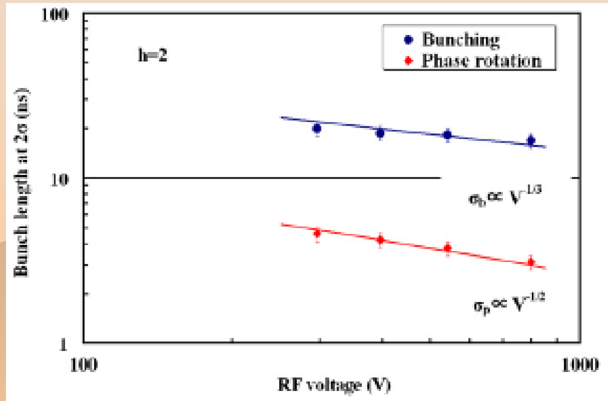
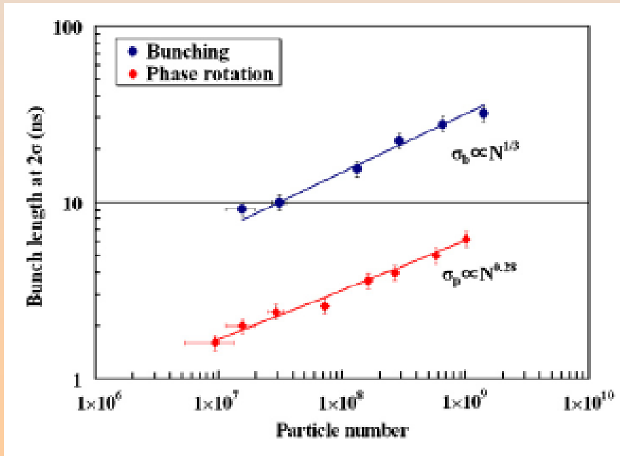
Short Pulse Formation at S-LSR with Electron Beam Cooling

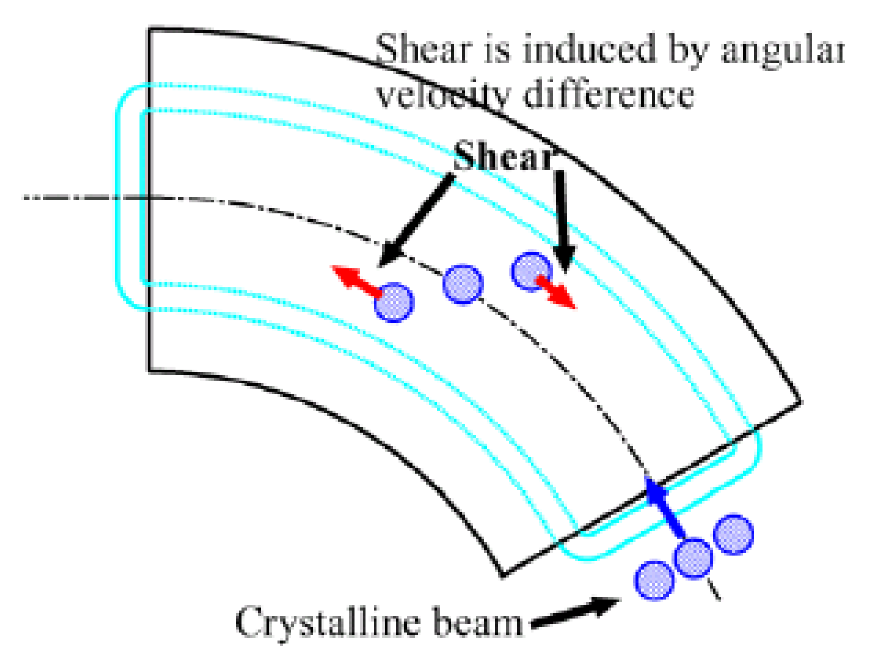


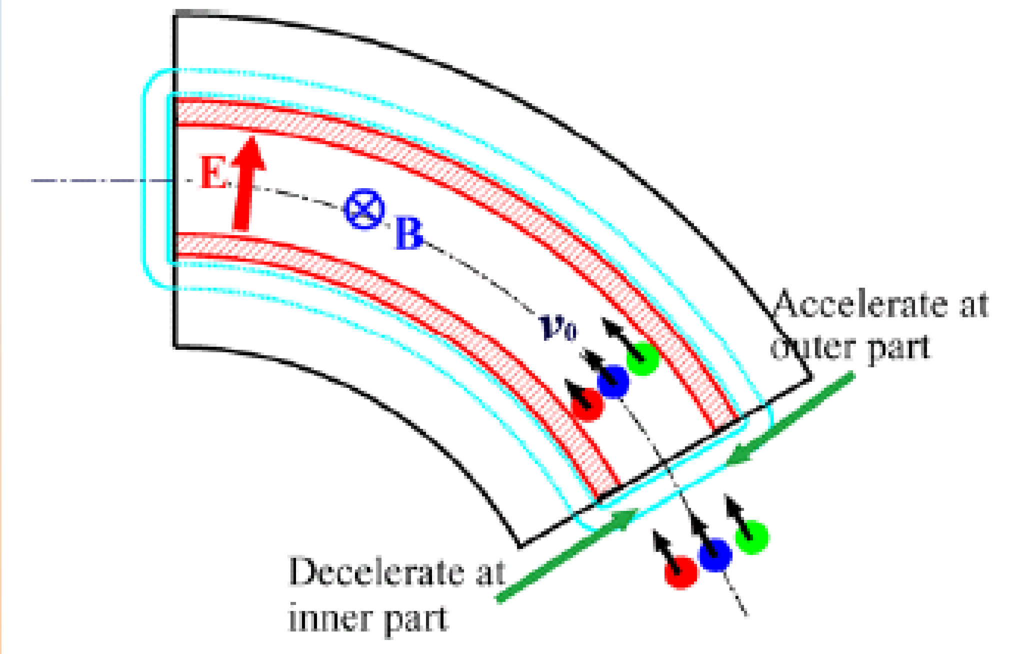






Shear Heating and Dispersion Suppressor





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

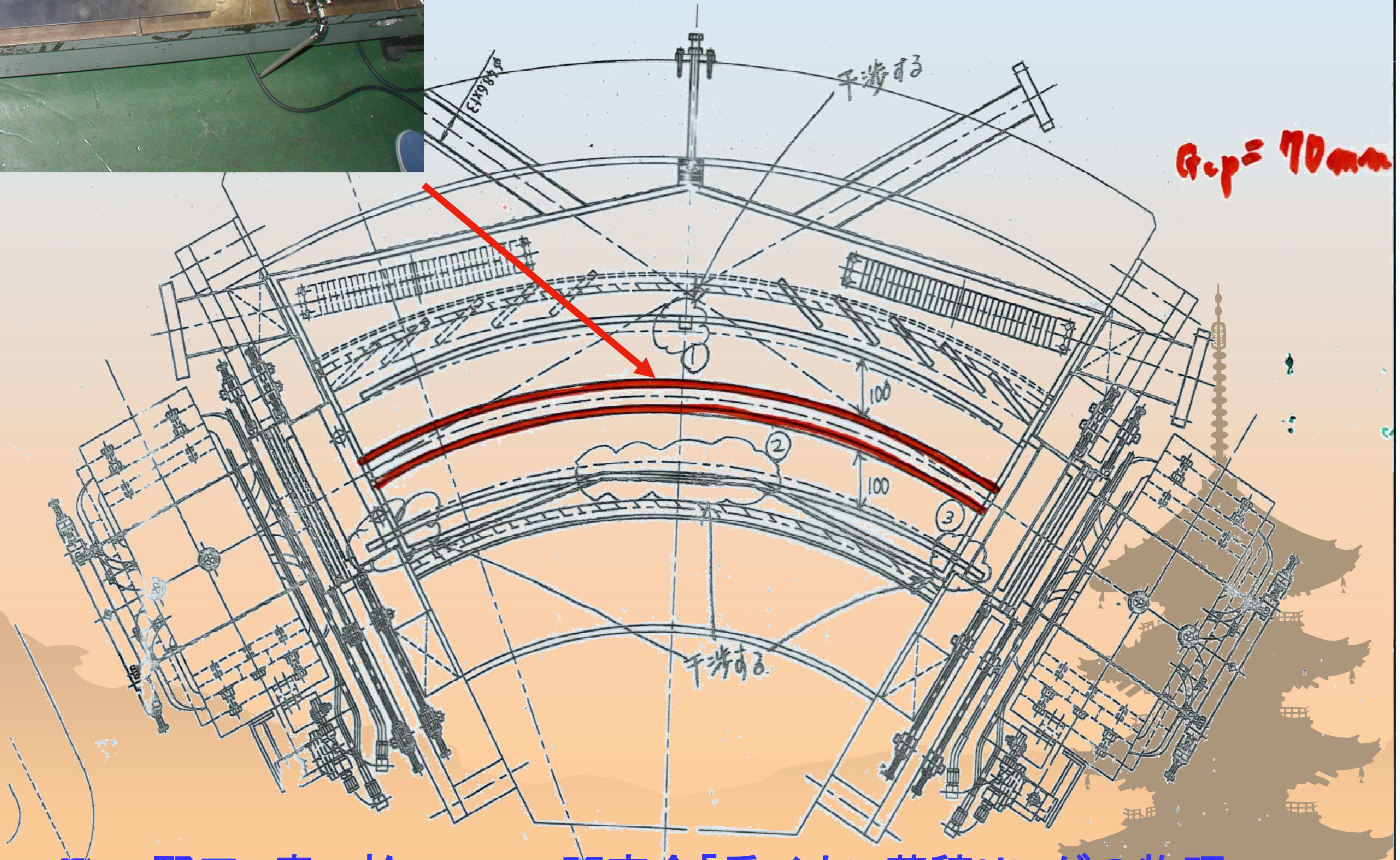
$$\frac{\Delta W}{W}=2\frac{\Delta P}{P}$$

Non-relativistic Case

↓

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

Vacuum Chamber in the Magnet Section (includes the Electrodes)



Summary

Storage Ring can contribute

- Intensity Increase for Heavier Ions with relatively low peak Ion Source Intensities
- Increase of Phase Space Density by Application of Beam Cooling
- Create Short Bunch Structure by Bunched Beam Electron Cooling

Thank you for your kind Attention!!