ハドロン加速器ビーム増強のための誘導加速装置の開発

高山　健
加速器研究施設
高エネルギー加速器研究機構

質量起源と超対称性物理の研究会
2003年 3月5日

Key Words: スーパーバンチ, 誘導加速シンクロトロン
スーパーバンチ・ハドロンコライダー

目次

1　背景、目標、意義

背景：今回の研究の主体になるメンバーは

1986-1995 電子線形誘導加速器を用いてマイクロ波自由電子レーザー(FEL)の開発に従事

主たる成果：世界初のイオンチャネルガイド x-band FELを実現する（出力100MW, ゲイン26dB/m)。
世界初のPre-bunched x-band FEL を実現する（出力150MW, ゲイン76dB/m)。

1996-2000 K2K実験（KEKとスーパーカミオカンデを結ぶ長基線ニュートリノ振動実験）
に向けて12GeV PSビーム強度の増強プログラムに取り組んだ。実験継続中

主たる成果：ビーム強度の倍増　(4×10^{12}ppp-> 8×10^{12}ppp)を実現。99%の確証で振動を確認

1999-　誘導加速シンクロトロンの原理を発表する。
必要なデバイスのR&Dを科研費等の支援を受け東京工大、国内メーカーと共同で推進中。

2001-　スーパーバンチハドロンコライダー(SHC)の概念を提案する。その理論的研究が進行中。

2001.6　米国 Snowmass 2001会議で SHC はVLHC の有力なオプションとして認知される。

2002.6　ヨーロッパ加速器会議でCERN 自身がLHC のアップグレード案としての SHCの検討を報告

2002.10　KEK で「誘導加速器の進展」と題して国際ワークショップを開催

目標：今後２、３年内に必要なデバイス製作し、提案するシナリオに沿って、KEK-12GeV 陽子シンクロトロンで スーパーバンチ加速実証試験を行うと共にその応用を考究する。

意義：既存加速器の全体構成を大幅に変える事なく、今までのRFシンクロトロンでは原理的に使用が不可能であった縦方向の空間領域にビームを詰め込み、加速するのでビーム強度を大幅に増強する事が可。この誘導加速／閉じ込め方式は全ての大型ハドロン加速器が50年来依って立ったRF加速方式に置き換わる可能性。

近未来の期待　KEK12GeV-PS、統合計画3GeV/50GeVリングの増強 -> マルチメガワット加速器に
BNL, CERN, FNAL既存加速器群でのビーム増強 -> Higgs 粒子発見の大きな可能性

中期／長期　ハドロンコライダー (LHC, VLHC) のルミノシテイーの大幅な増大 -> 20年の実験を1年で

Induction acceleration looks to the future

It was a milestone event in the history of induction accelerators when more than 55 experts assembled at KEK in October 2002 for an international workshop on Recent Progress in Induction Accelerators – RPIA2002.

The participants of the Recent Progress in Induction Accelerators Workshop, which was held at KEK on 29–31 October 2002.

They came from 15 different institutes and three private companies. Their purpose: to discuss recent progress in induction accelerators and the key technologies that are common to the different communities of heavy-ion inertial fusion and high-energy accelerators. The workshop focused on four topics:

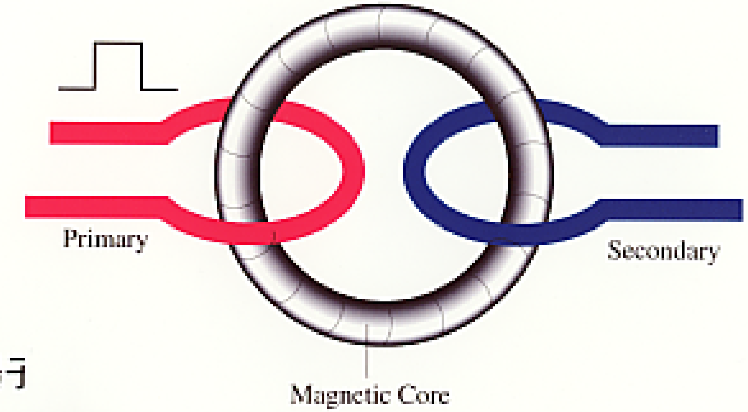
- A review of developments in induction acceleration since the first demonstration by Nicholas Christofilos, applications, and up-to-date activities in energy research and high-energy physics.
- New concepts and ideas using induction acceleration.
- Key technologies, such as magnetic materials and solid-state modulators, which are indispensable for the realization of high-gradient accelerating fields and low-loss, high rep-rate operation.
- Beam dynamics specific to extremely high-intensity beam linacs, circular induction accelerators and hadron colliders employing a so-called super-bunch.

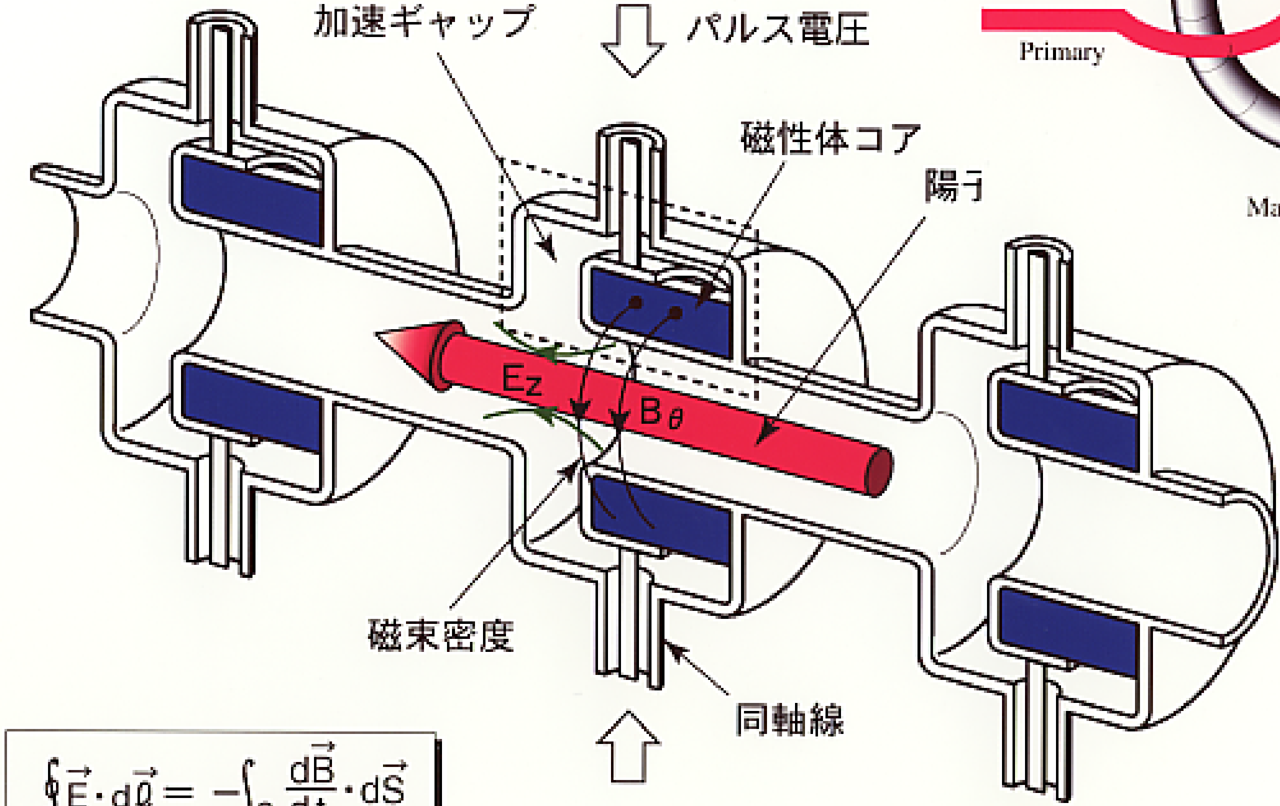
In his welcome address, Hirotaka Sugawara, director-general of KEK, stressed the importance of investment in accelerator R&D when he talked of the recent activities of ICFA as well as the status of ongoing and future projects at KEK.

The review of the history of induction accelerators ranged from the late 1960s with the first machine, ASTRON, to the recent Advanced Test Accelerator and Experimental Test Accelerator at the Lawrence Livermore National Laboratory (LLNL). A large variety of applications were also reviewed, from early applications to electron ring acceleration and high-power microwave generation. More recently, electron induction linacs have successfully demonstrated their capability as high-intensity electron beam drivers for free-electron lasers (at LLNL, KEK, the Japan Atomic Energy Research Institute (JAERI) and CESTA in France), as a relativistic klystron at LLNL/LBNL, and as a backward wave oscillator at JAERI.

The Virtual National Laboratory (VNL) in the US has recently focused on R&D work for a heavy-ion inertial fusion driver, using 4 GeV bismuth beams, with a 2 kA/beam and a 10 ns pulse length. The workshop heard about the US Heavy Ion Fusion Accelerator Program, which is concentrating on three areas: source/injector development, low energy transport, and neutralization in ballistic focusing. The goals and key issues of an Integrated Beam Experiment, which is planned to verify the concept, were also discussed. A complementary simula-

誘導加速の原理

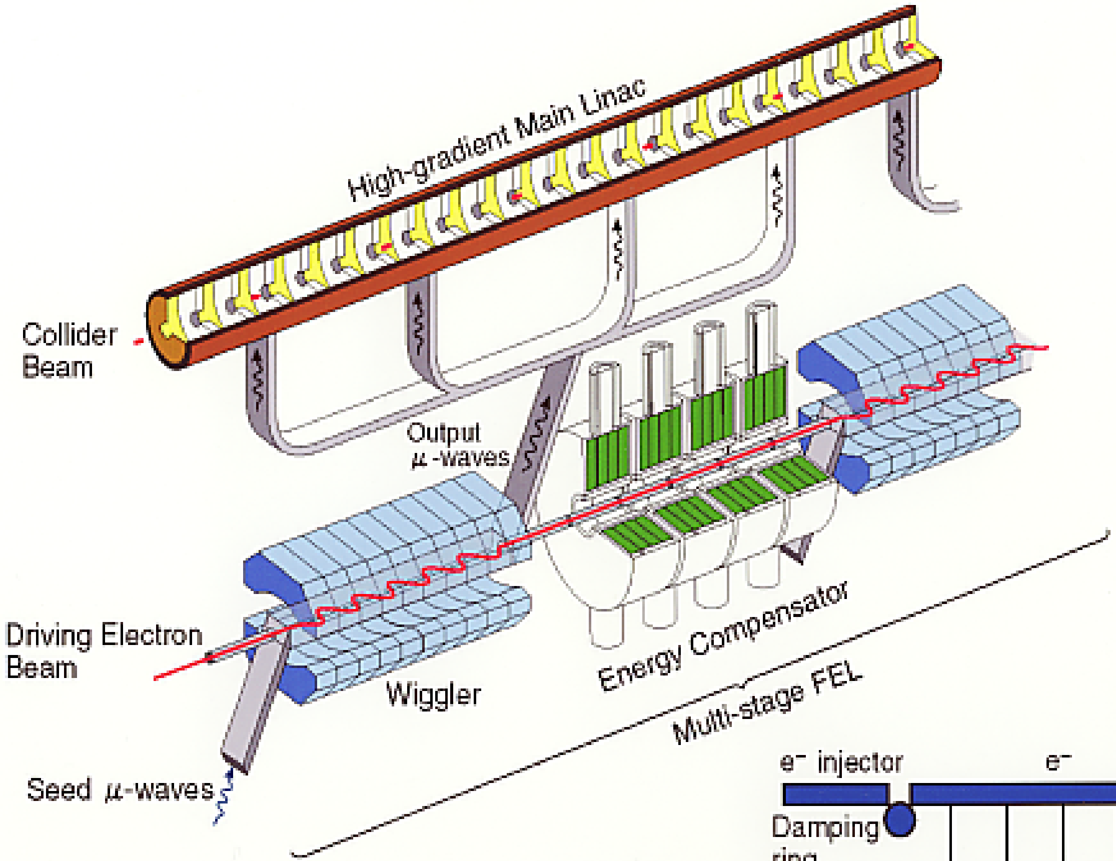


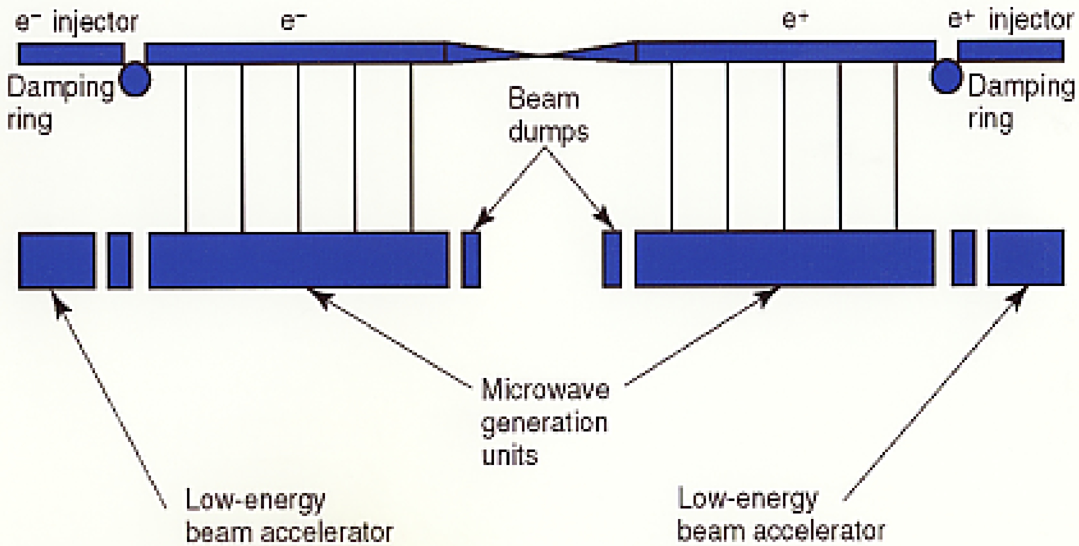


$$\oint \vec{E}\cdot d\vec{\ell} = -\int_S \frac{d\vec{B}}{dt}\cdot d\vec{S}$$

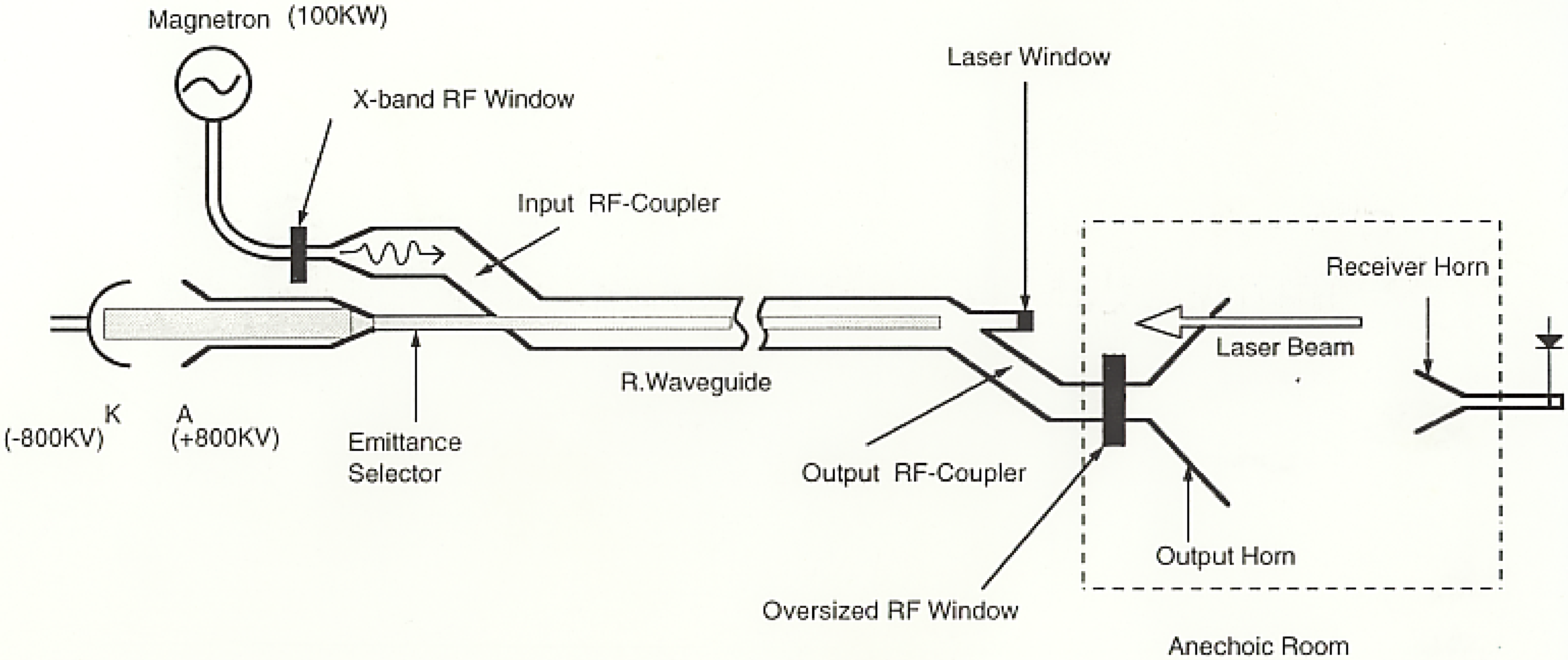
ファラディーの誘導法則

FEL-TBA

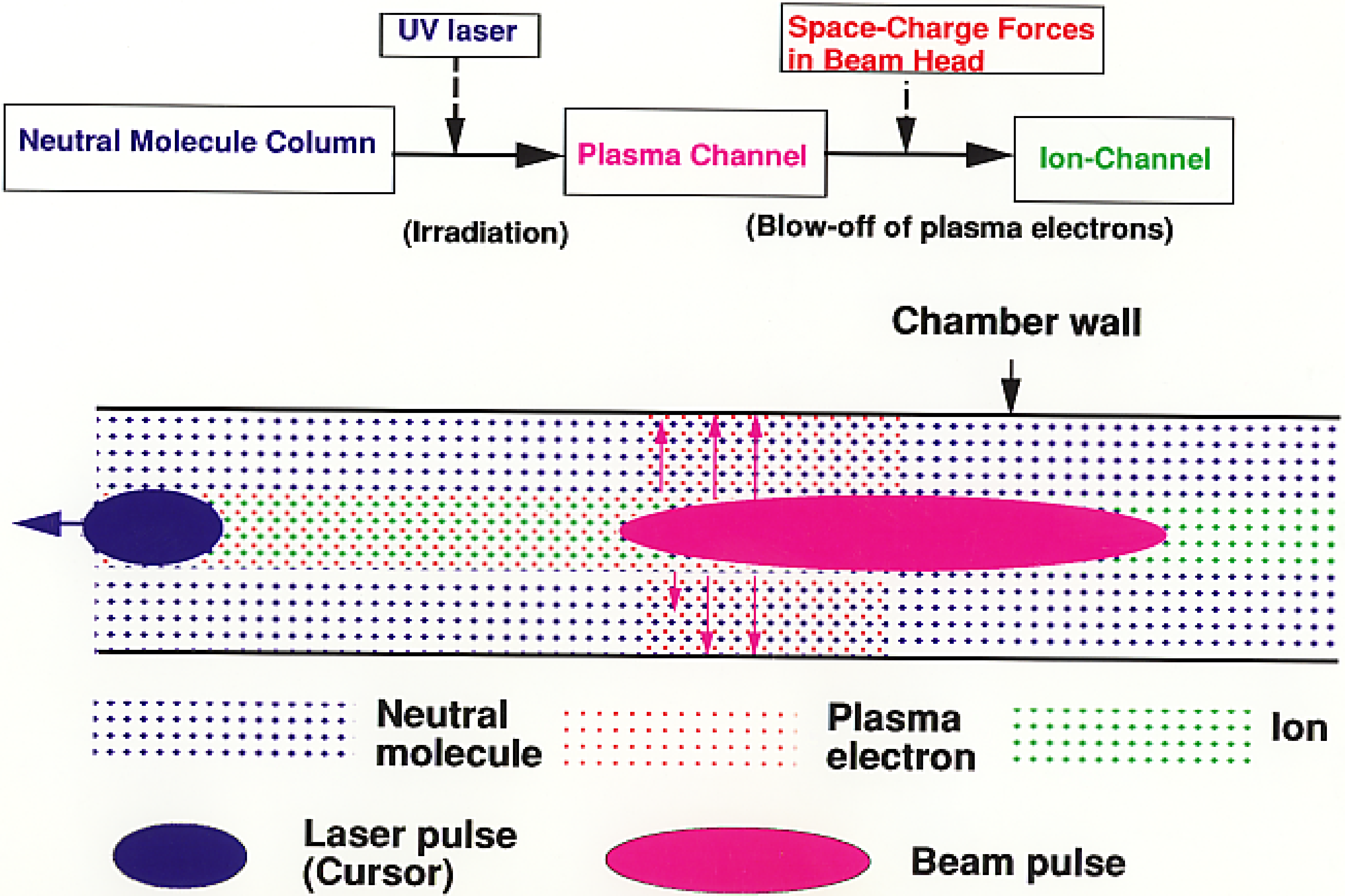

High-gradient Main Linac
Collider Beam
Output μ-waves
Driving Electron Beam
Wiggler
Energy Compensator
Multi-stage FEL
Seed μ-waves


e⁻ injector
e⁻
e⁺
e⁺ injector
Damping ring
Beam dumps
Damping ring
Microwave generation units
Low-energy beam accelerator
Low-energy beam accelerator

Ion-Channel Guided X-band FEL



Principle of Ion-Channel Guiding



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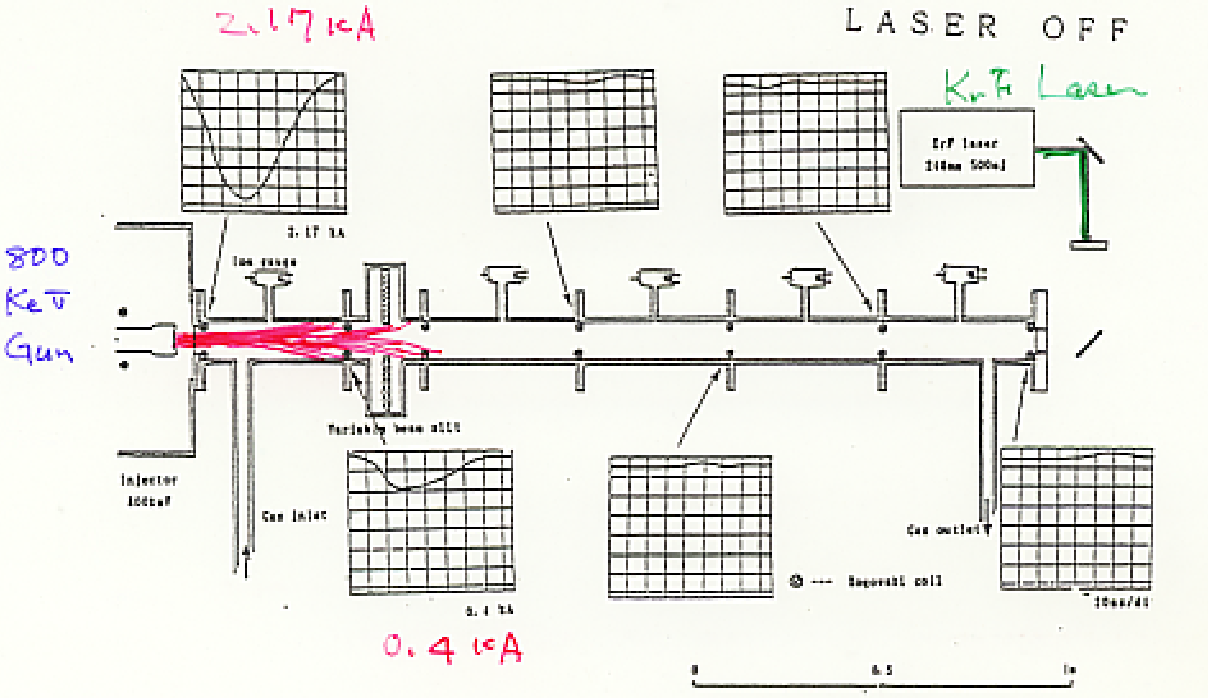
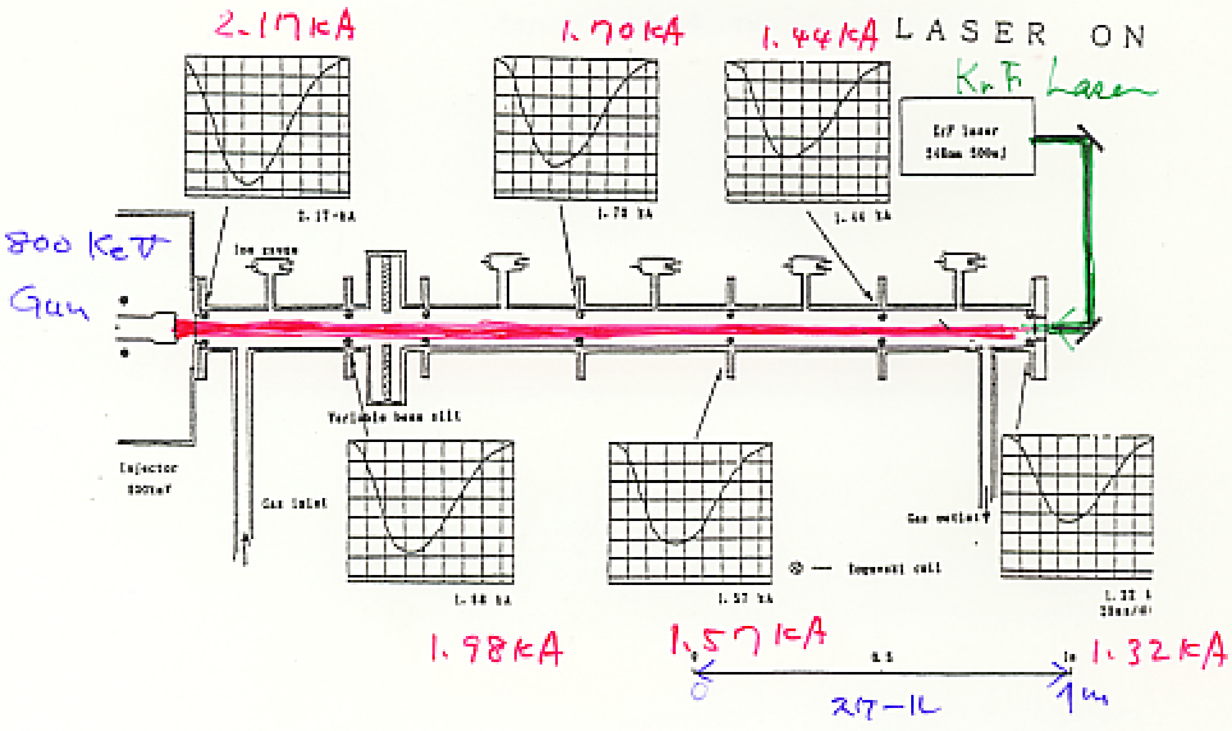
Experiment(800keV)



laser off , DEA pressure 4.0×10^{-4}



laser on , DEA pressure 4.0×10^{-4}

図3.12　KEKマイクロ波FELテストスタンドでのイオンチャンネルガイディング
全長2m　6ヶ所に置かれたロゴスキーコイルで見たビーム電流プロフィール
（ビームエネルギー 800kV、アノード電流 2.17kA）

Beam-Break Up Instability & Landau Damping

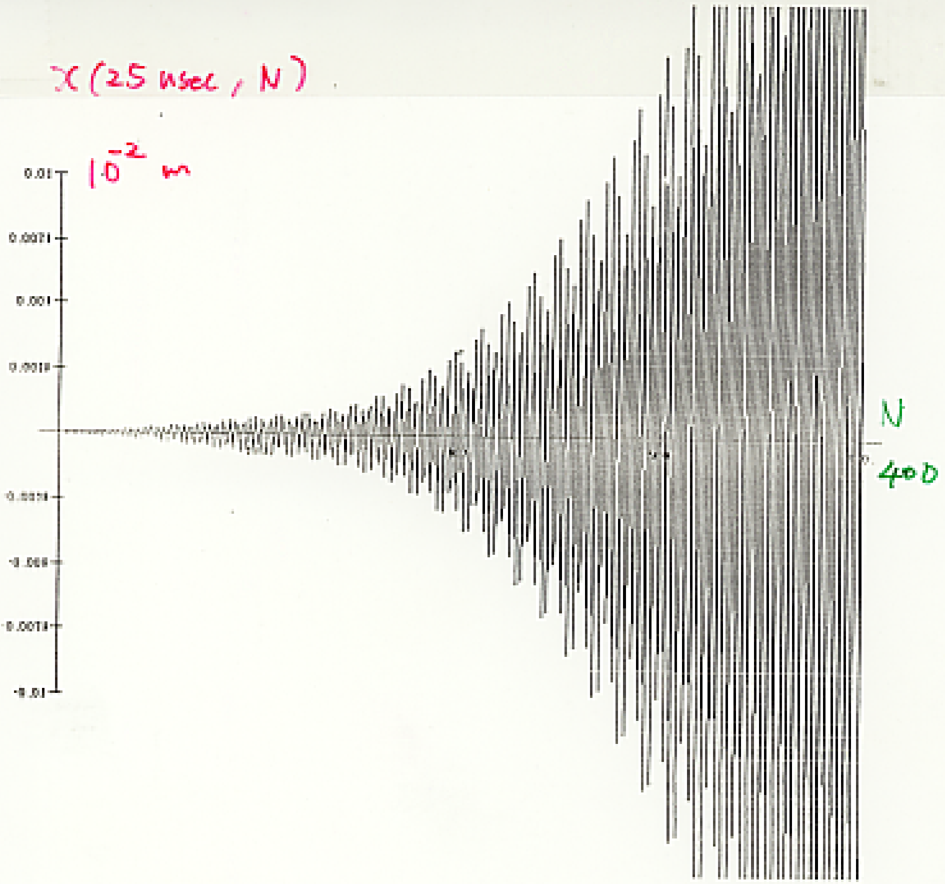
Ion Channel Radius

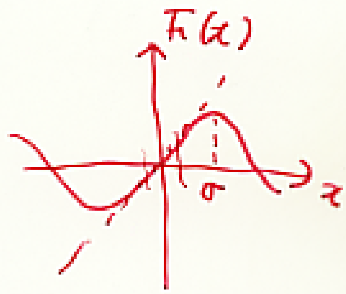
↓

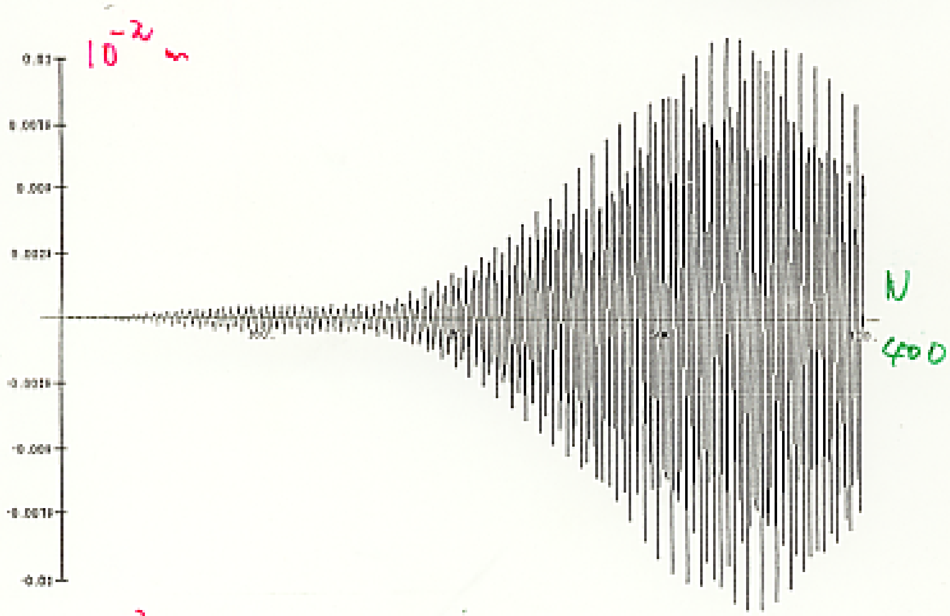
$R = \infty$ cm / 1σ

$\partial E_r / \partial r |_{r=0}$ = constant

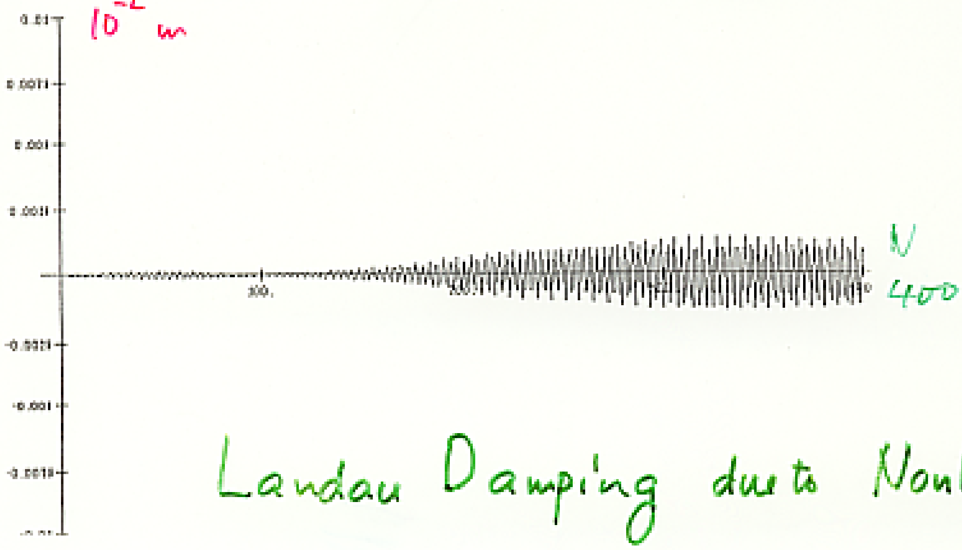
for 3 cases





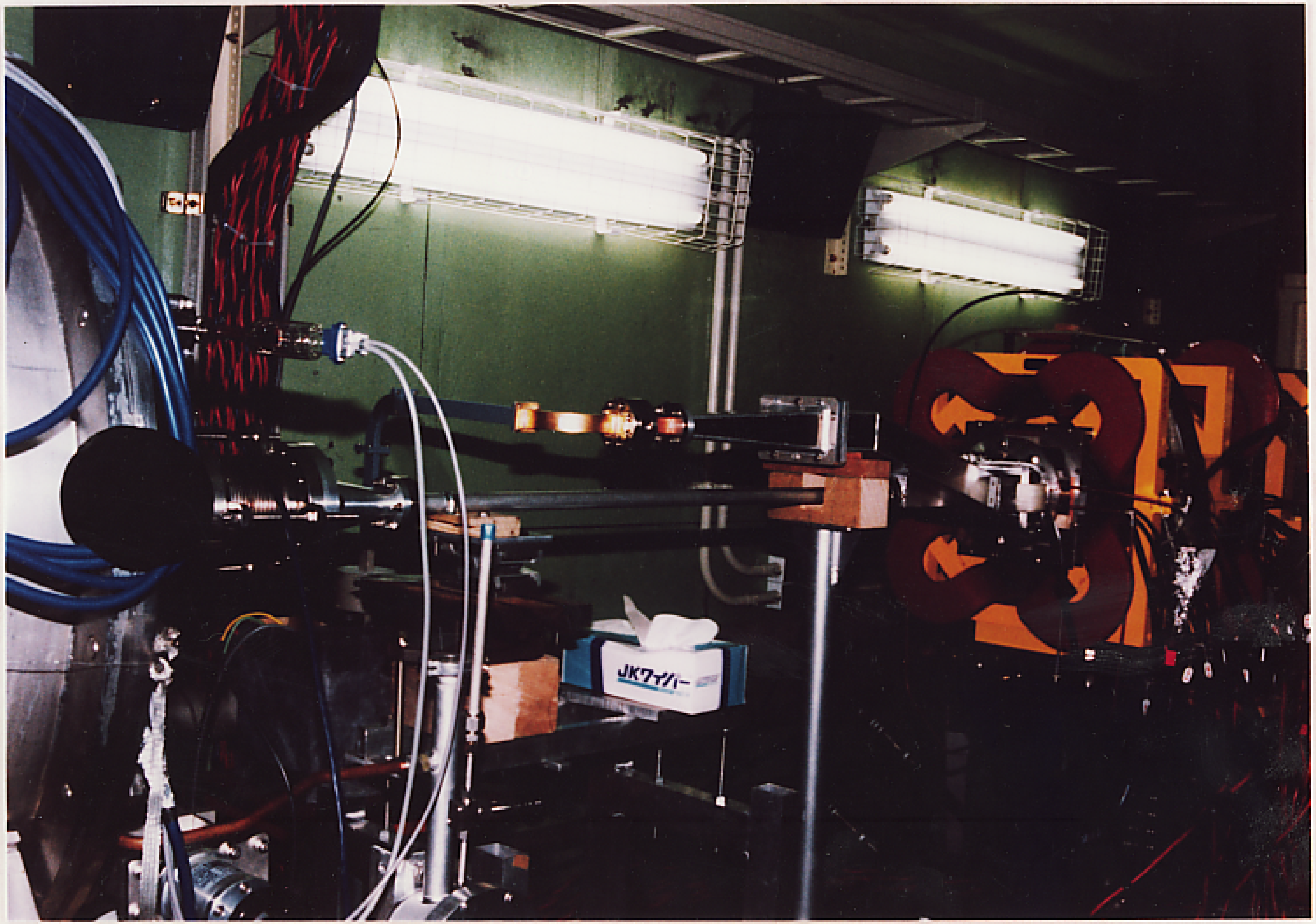


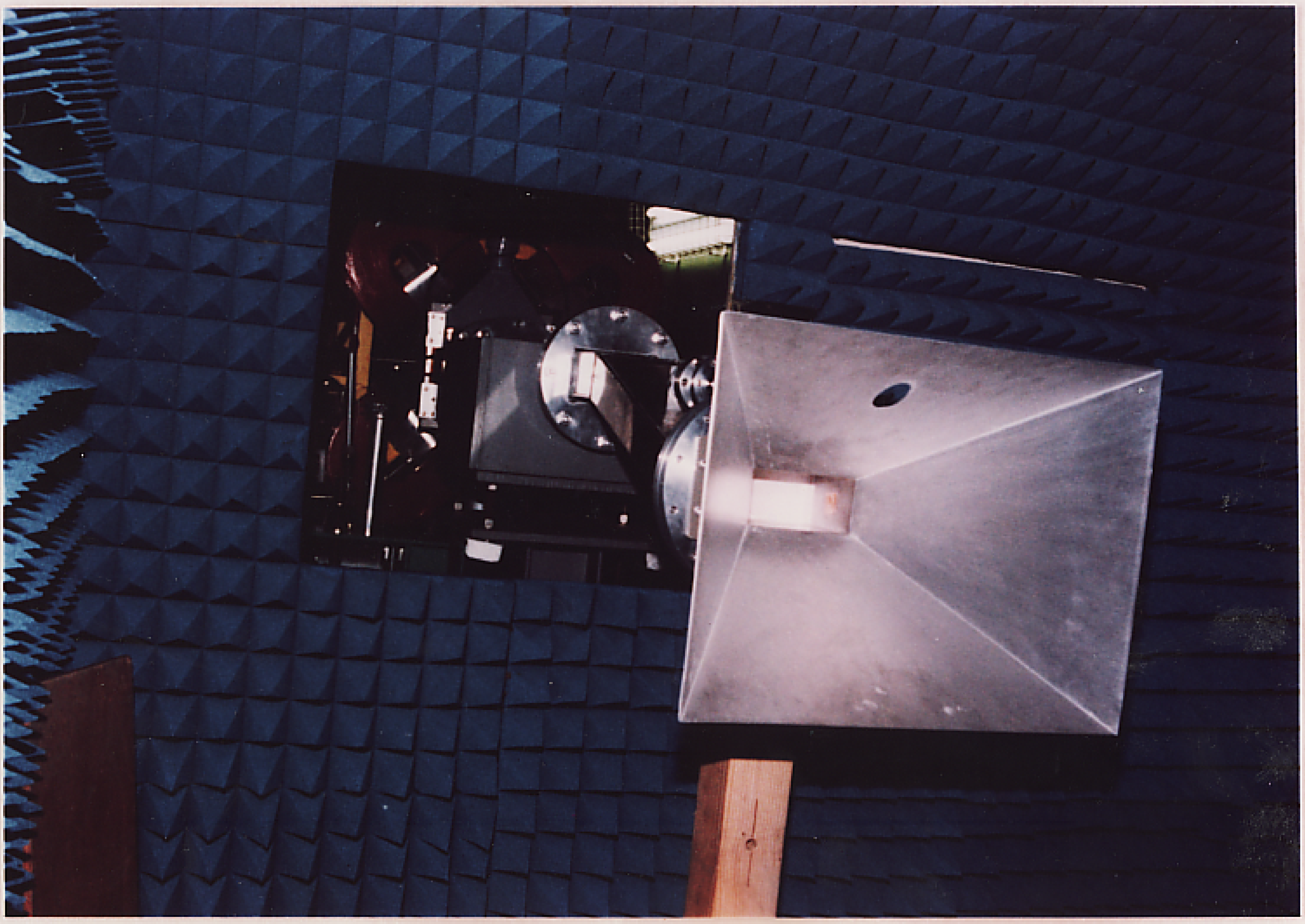
R = 1 cm / 1σ

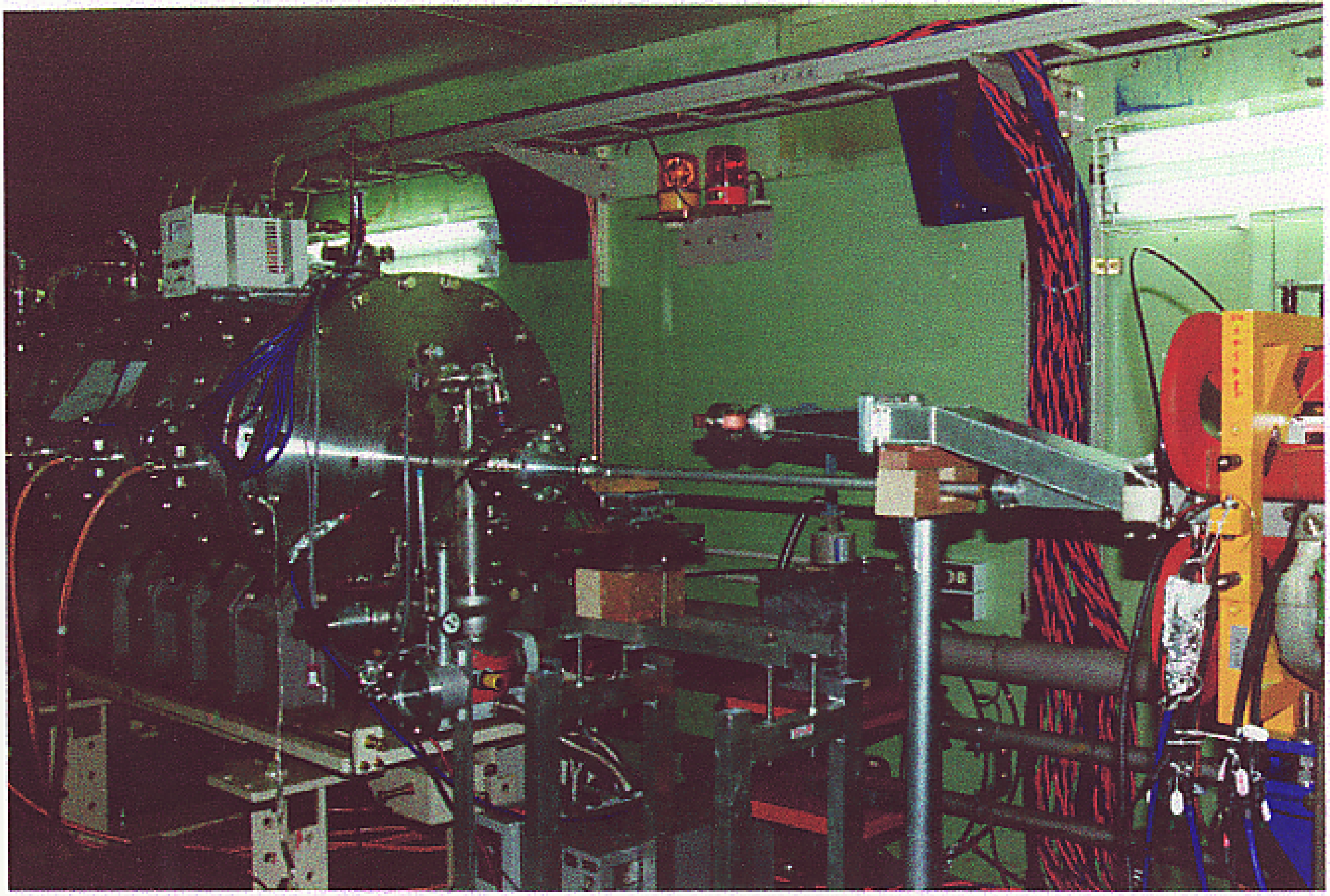


R = 2 mm / 1σ

Landau Damping due to Nonlinearity in Focusing


JKワイパー





Characteristics & Parameters

- **Distingushed from other 1MeV-class μ-FELs:**
  - Ion channel guiding(ICG) from e-Gun through wiggler.
  - Eddy-current assisted planar wiggler.
  - Efficient *Over-sized* input and output couplers.

Wiggler	Period[cm]	16
	Length[m]	2.4
E-Beam	Energy[MeV]	1.5
	Current(In/Out)[A]	650/450
	Acceptance[cm rad]	0.06-0.04
Microwave	Frequency[GHz]	9.4
	Waveguide(axb)[cm]	11x5.5
	Seed power[kW]	77
	Mode	TE01
Ion-Channel	Ion density[10^{10} cm^{-3}]	2.0

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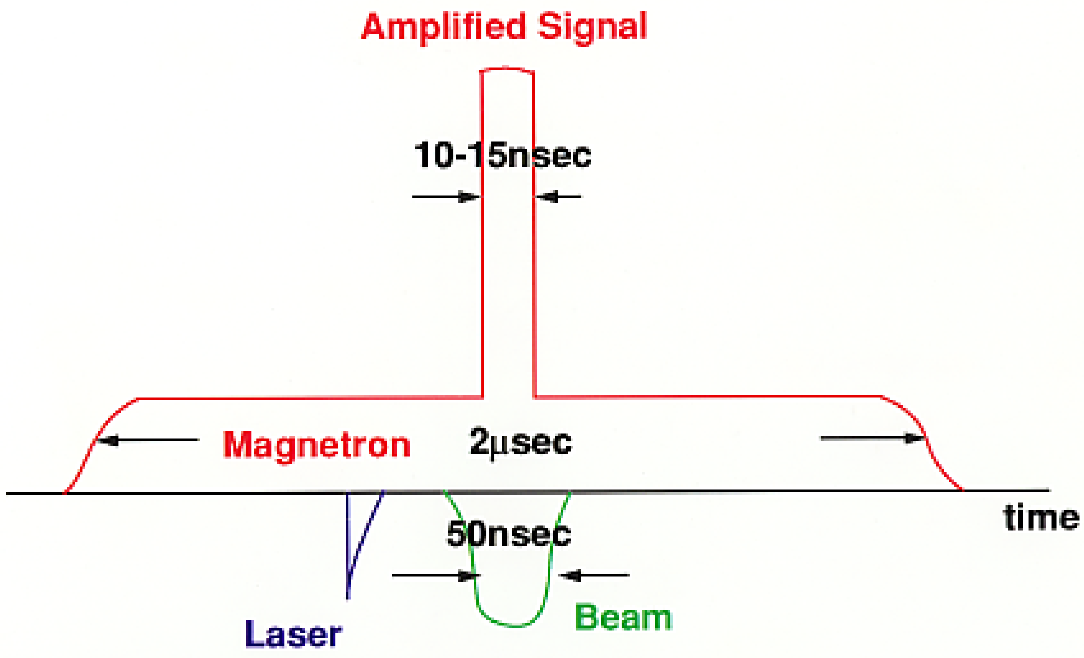

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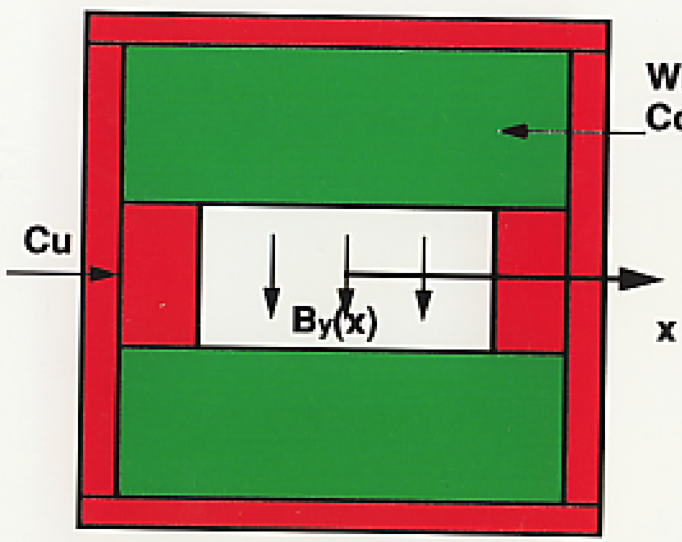
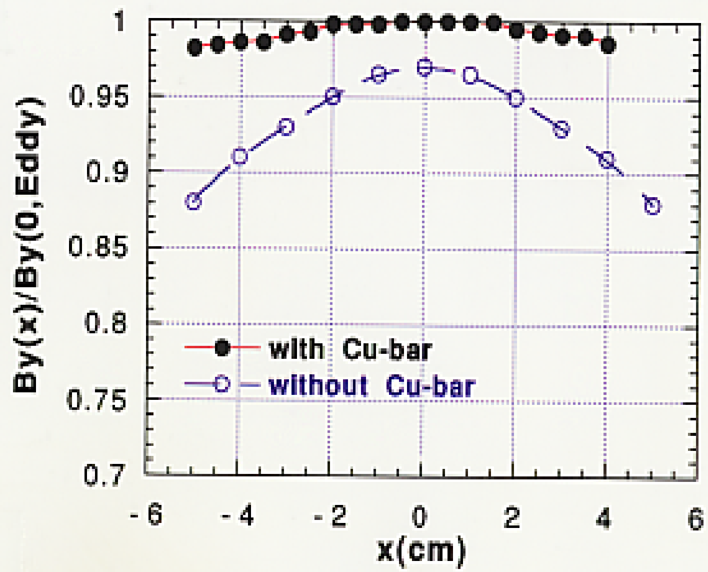
Wiggler

- **Pulse excited planar wiggler:** $\tau_{rise} \sim 5$ msec
  - **Air-core planar wiggle**r magnet (λ_W=16cm and 15 periods) independently energized with a pulse power-supply.
- **Eddy-current assisted field-uniformity:**
  - **ΔBw/Bw=1.5%** at the RW's horizontal edge.
  - provided with **thick copper bars** inserted in both sides of the wiggler gap





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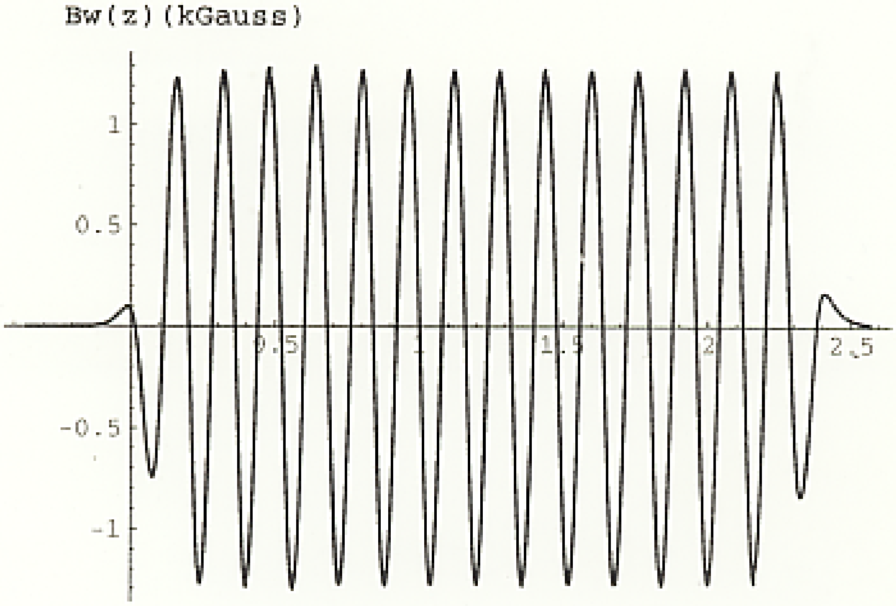
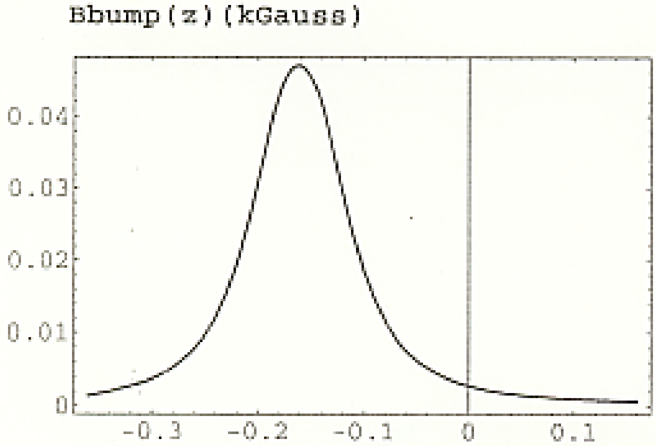
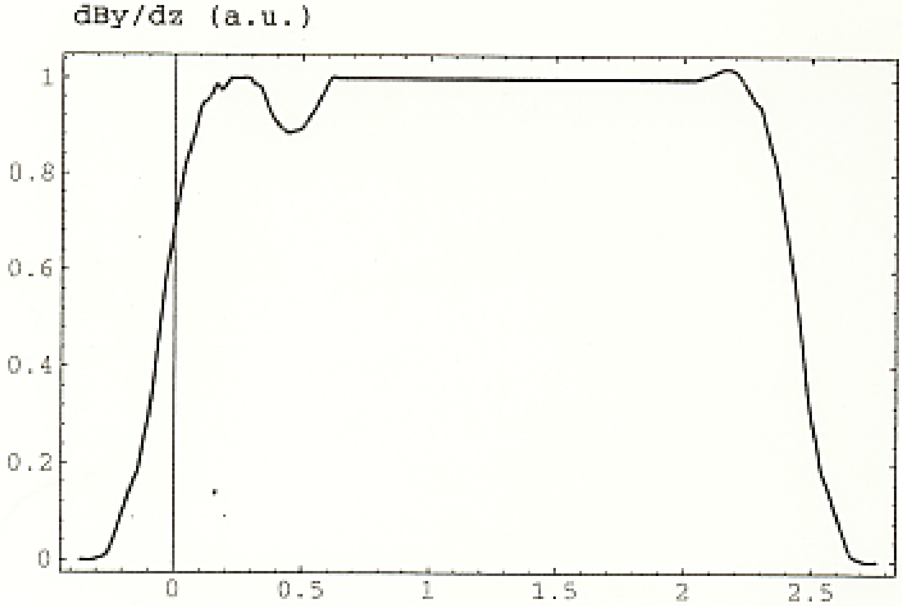

Bw(z)(kGauss)
1
0.5
-0.5
-1
0.5
1
1.5
2
2.5


Bbump(z)(kGauss)
0.04
0.03
0.02
0.01
0
-0.3
-0.2
-0.1
0
0.1


dBy/dz (a.u.)
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5

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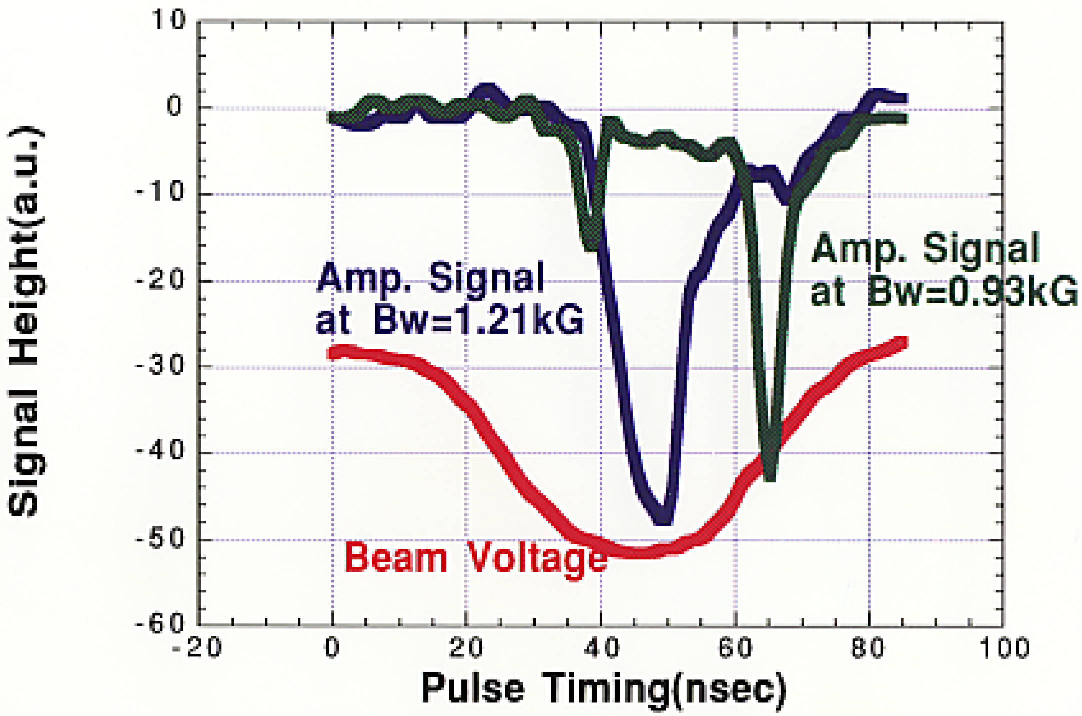
Resonant Structure in Signal

- **Resonant structure/Resonant beam energy:**
  Two resonant portions merge at the central position in beam votage pulse beyond Bw=1.2kG which gives the resonance for 1.5MeV beams.



Resonant Energy in FEL

$$\gamma_r = \sqrt{\frac{\omega_s}{2c}\cdot\frac{(1+a_w^2)}{(k_w-\delta k_s)}}$$

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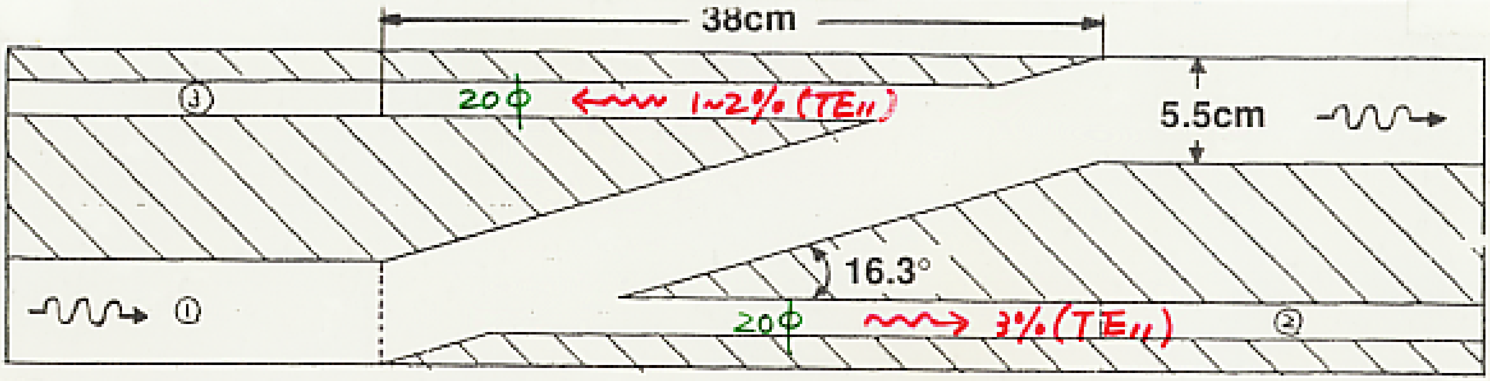
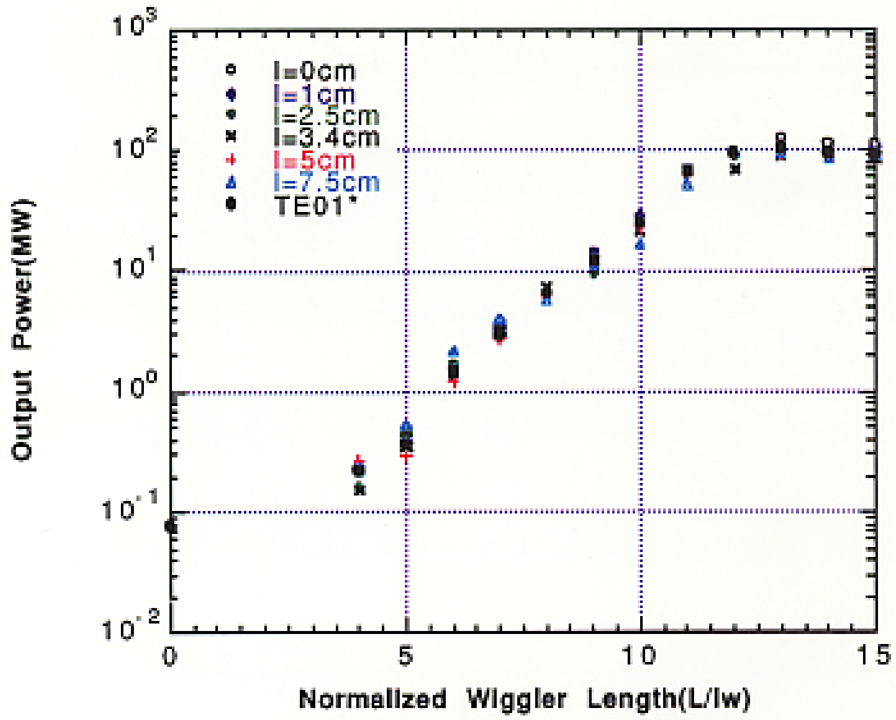
Oversized RF Components

- **Seed Power Source:** pulsed magnetron(EEV Model M5188) of 91kW.
- **Input/Output Coupler:**
  - **Miter-bends** to minimize **reflection** and **mode-conversion**, with a passing a small aperture for **electron beam/laser beam**.
- **Horn Antenna/Receiver:**
  - The transmitted μ-wave is emitted into the anechoic room.
  - Its fraction is received with the basic-size open-RW.
  - The radiation signal is attenuated down to the **milliwatt level** and monitored by a **crystal diode**.



Evolution

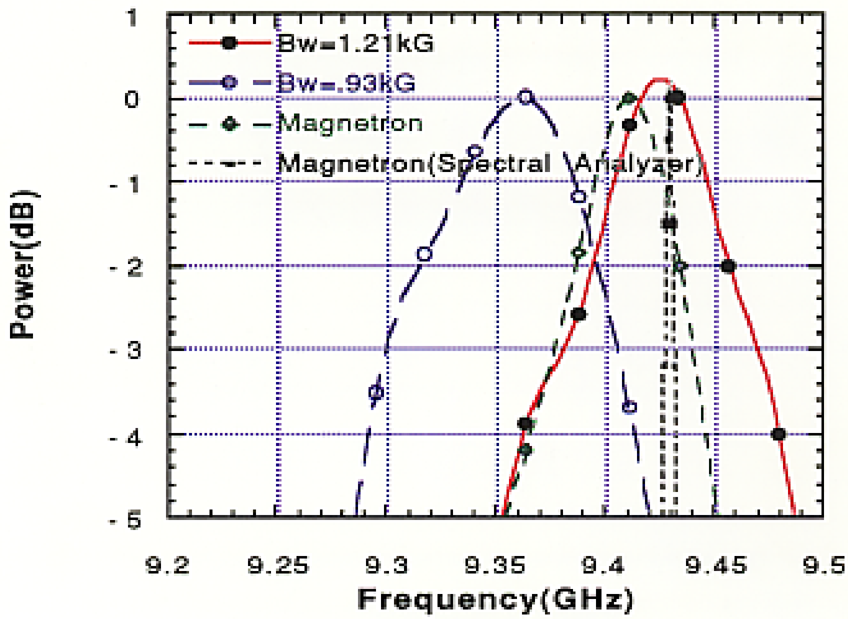
- **Evolution curve** obtained by simply turning on the wiggler unit in order.



- The evolution curve of TE01(dominant) adjusted by the **phase interference method**. **21dB/m.**
- A small fraction of the received power originate from **TE03 mode** converted in the output coupler including the RF-window.
- **TE21 mode** possibly evolving through the int. region rarely contributed to the received fraction.

Frequency Spectrum

- **Measurement by a low-Q transmission-type frequency counter(Q=120):**
  - **Filling time** of the counter cavity, **2Q/ω**, is about **4 nsec**(< **pulse duration** of **10-15nsec**).



Signal:	seed	$\Delta f/f$=0.1%	Meas.:	S.A.
	seed	0.6%		F.C.
	Amp.	0.9%		F.C.

- **Another notable result**:
  - **Down-shift in the frequecy spectrum for detuned amplified power(B_W=0.93kG), - 60MHz.**

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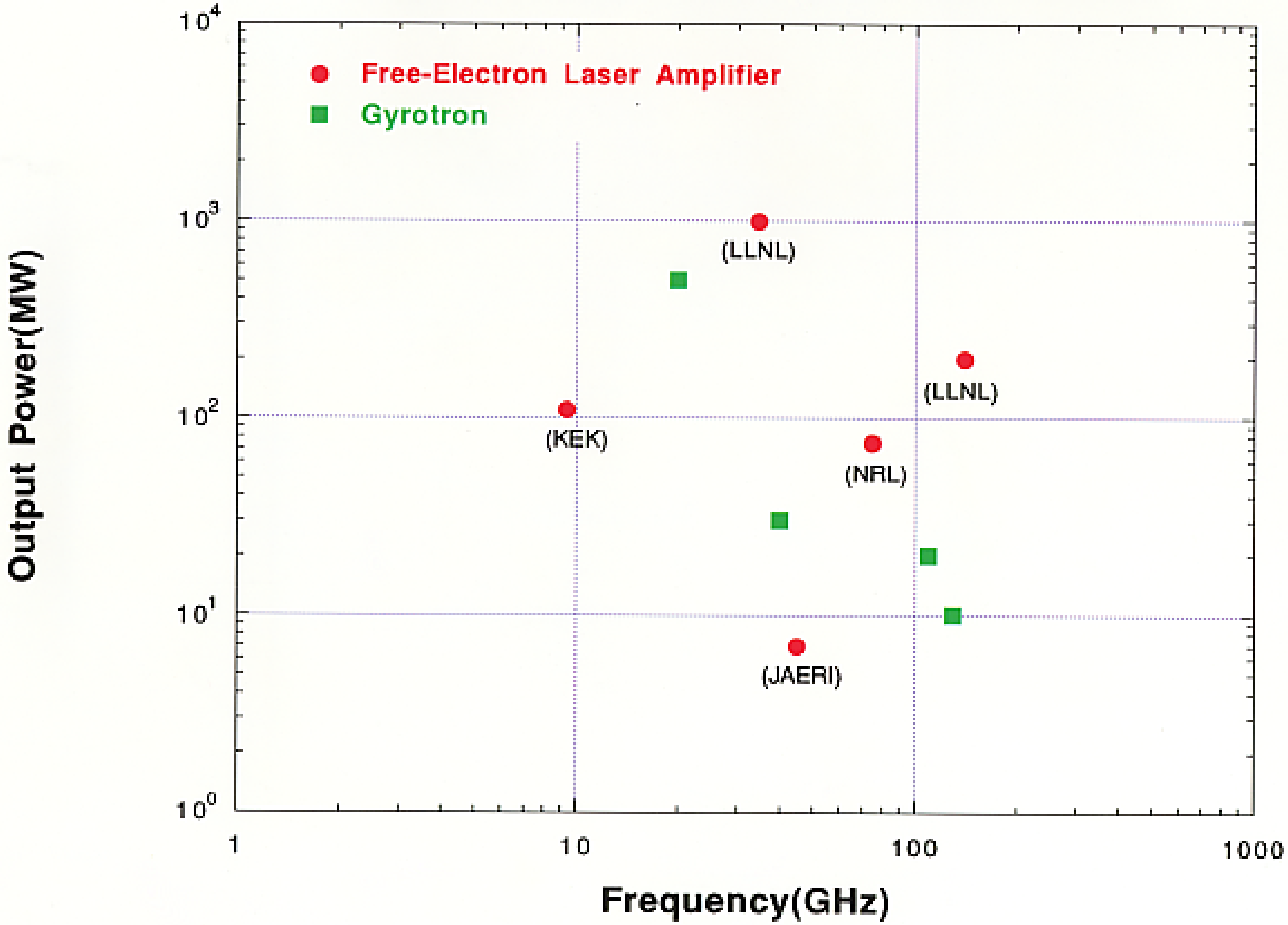
High Power Sources in the World



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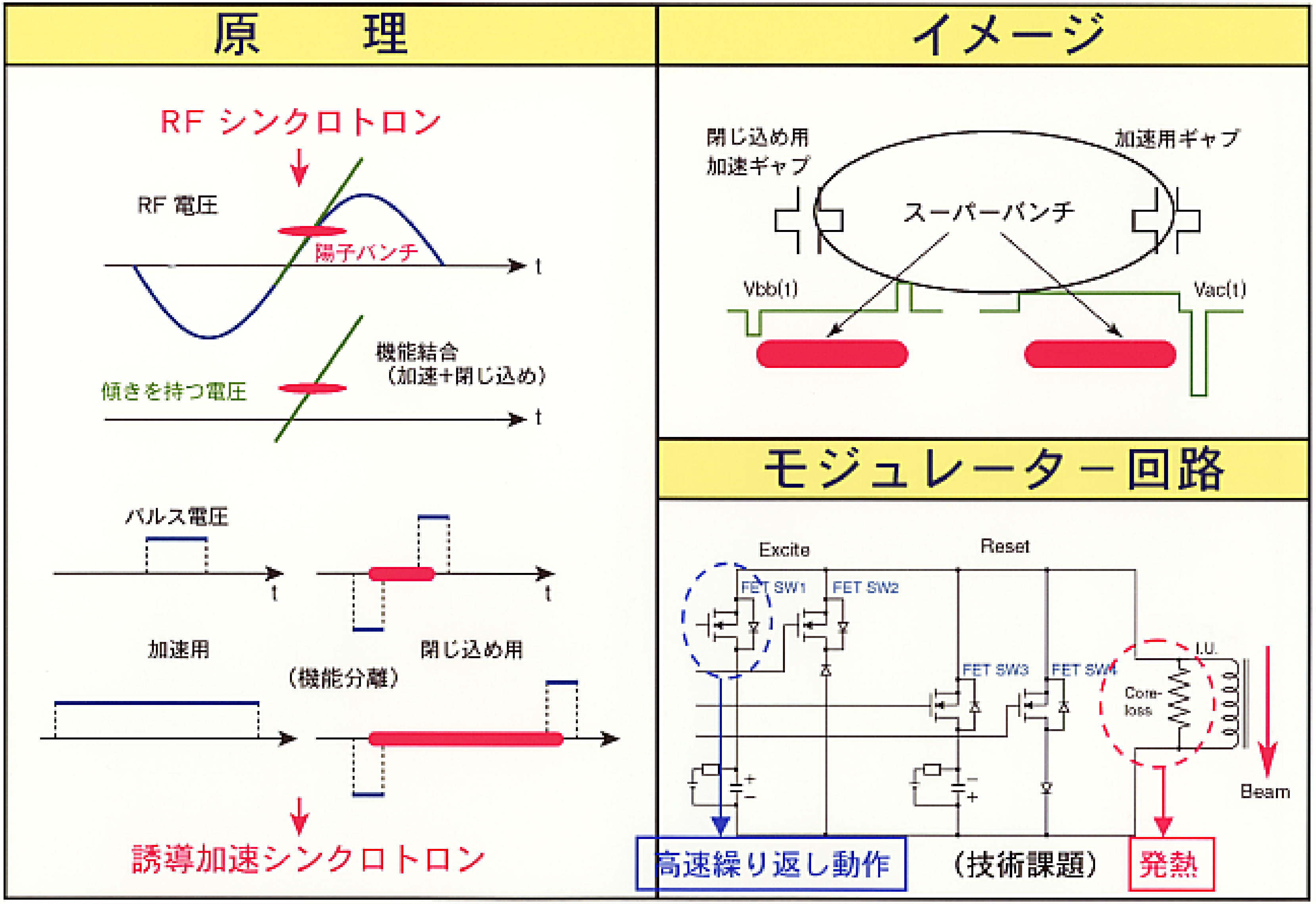
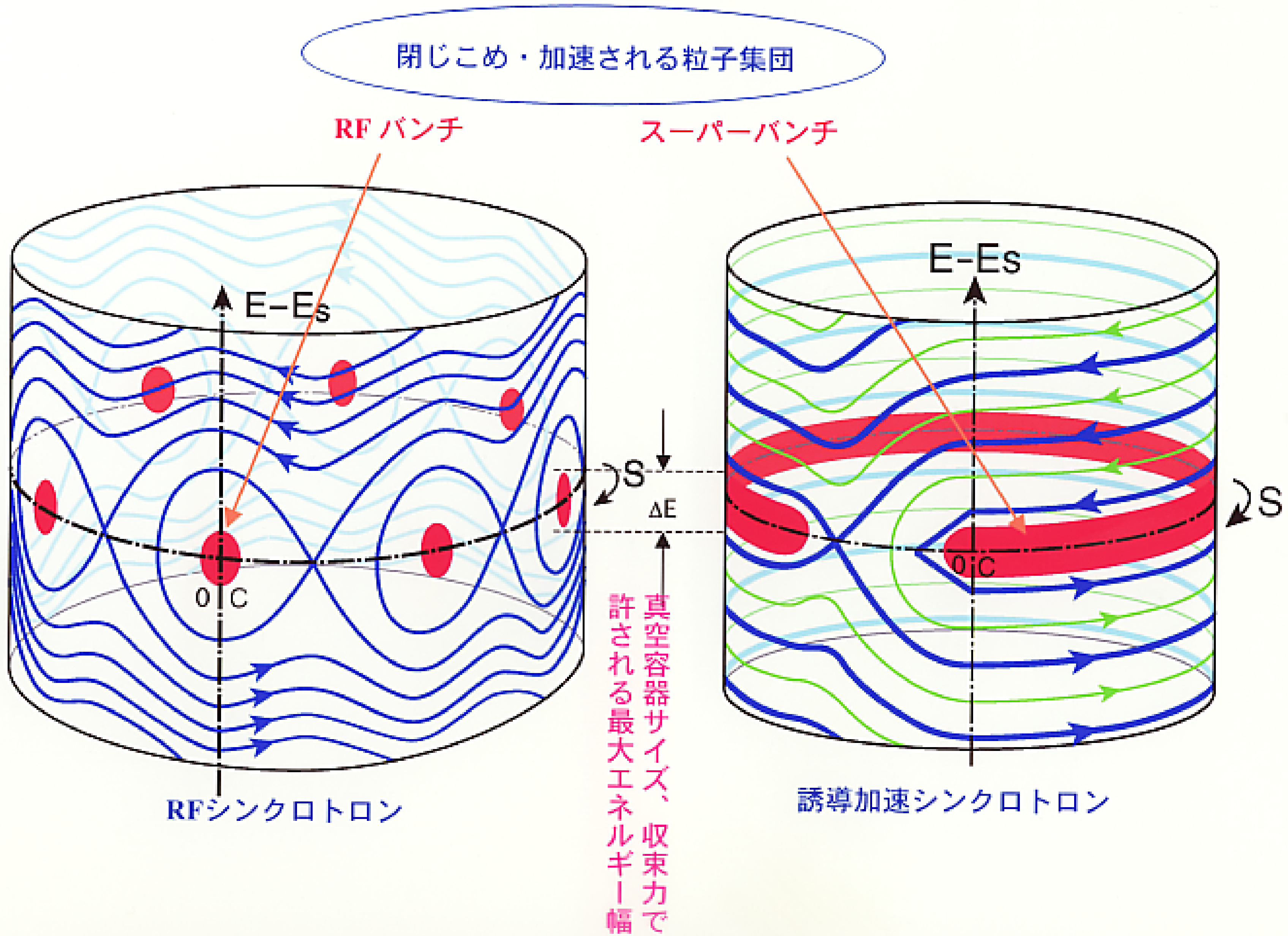
誘導加速シンクロトロンの概念

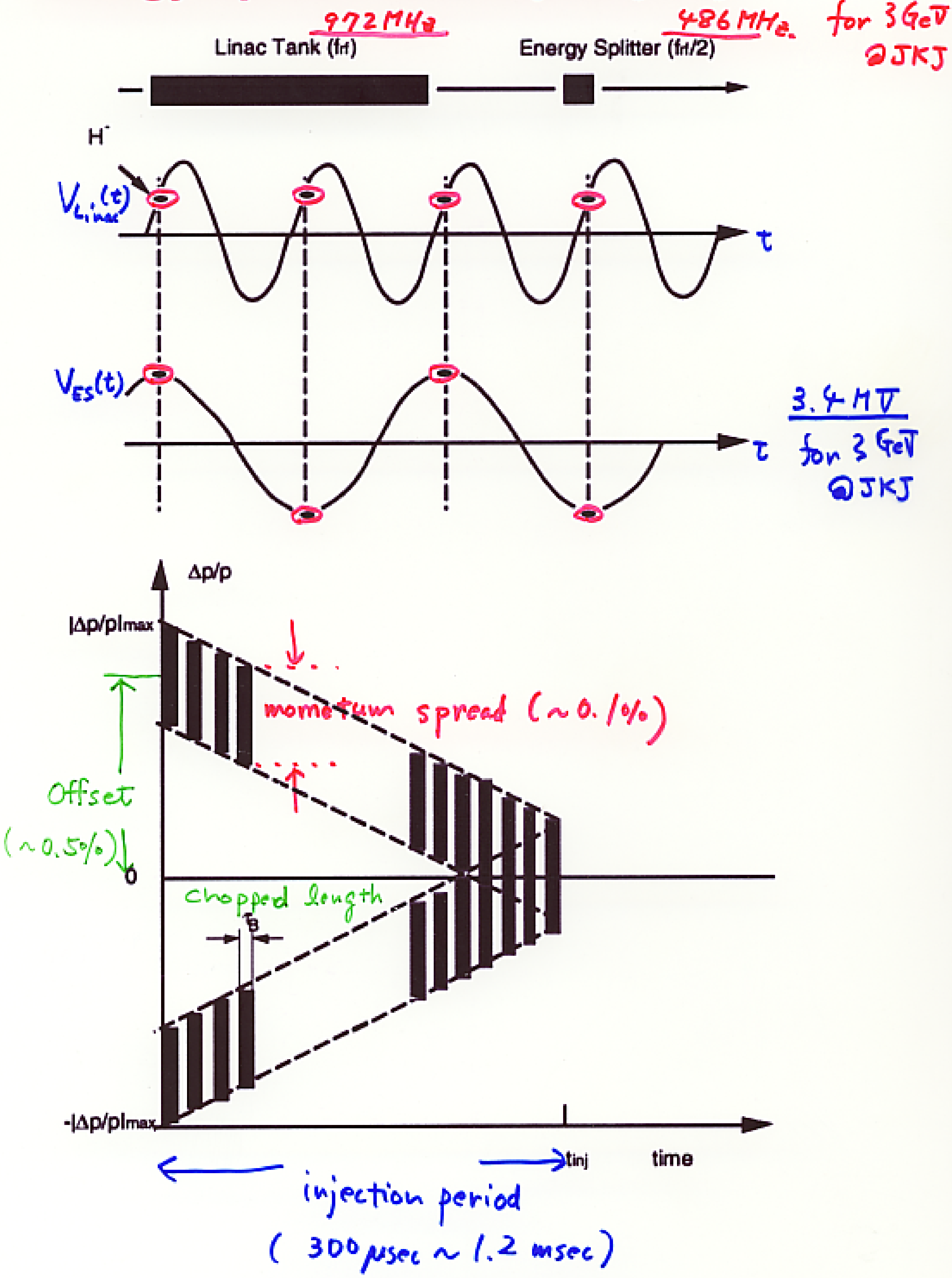


K.Takayama and J.Kishiro, "Induction Synchrotron", *Nucl. Inst. Meth.* A451, 304 (2000).

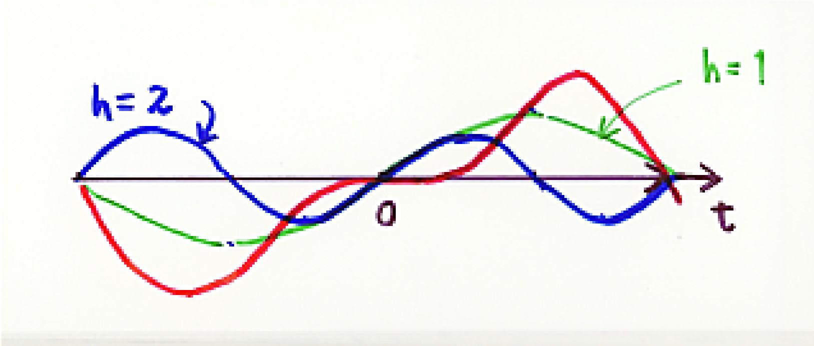
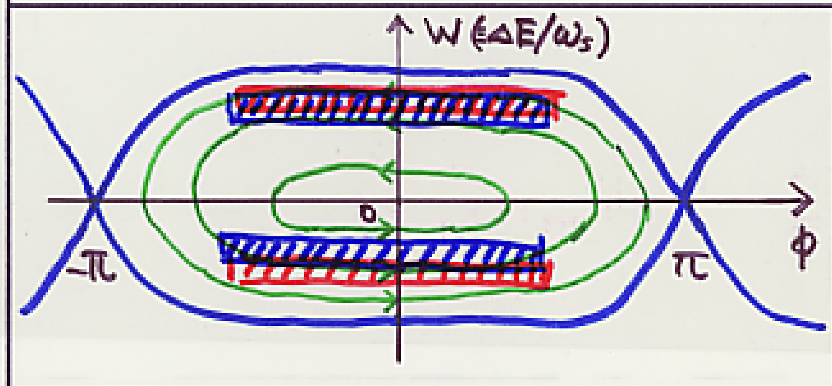
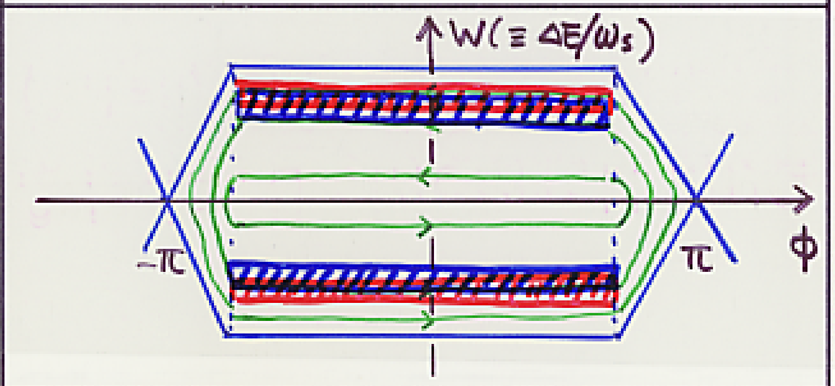
位相空間で見る RF シンクロトロンと誘導加速シンクロトロンの違い



Energy Splitter and Flip-flop Inj.

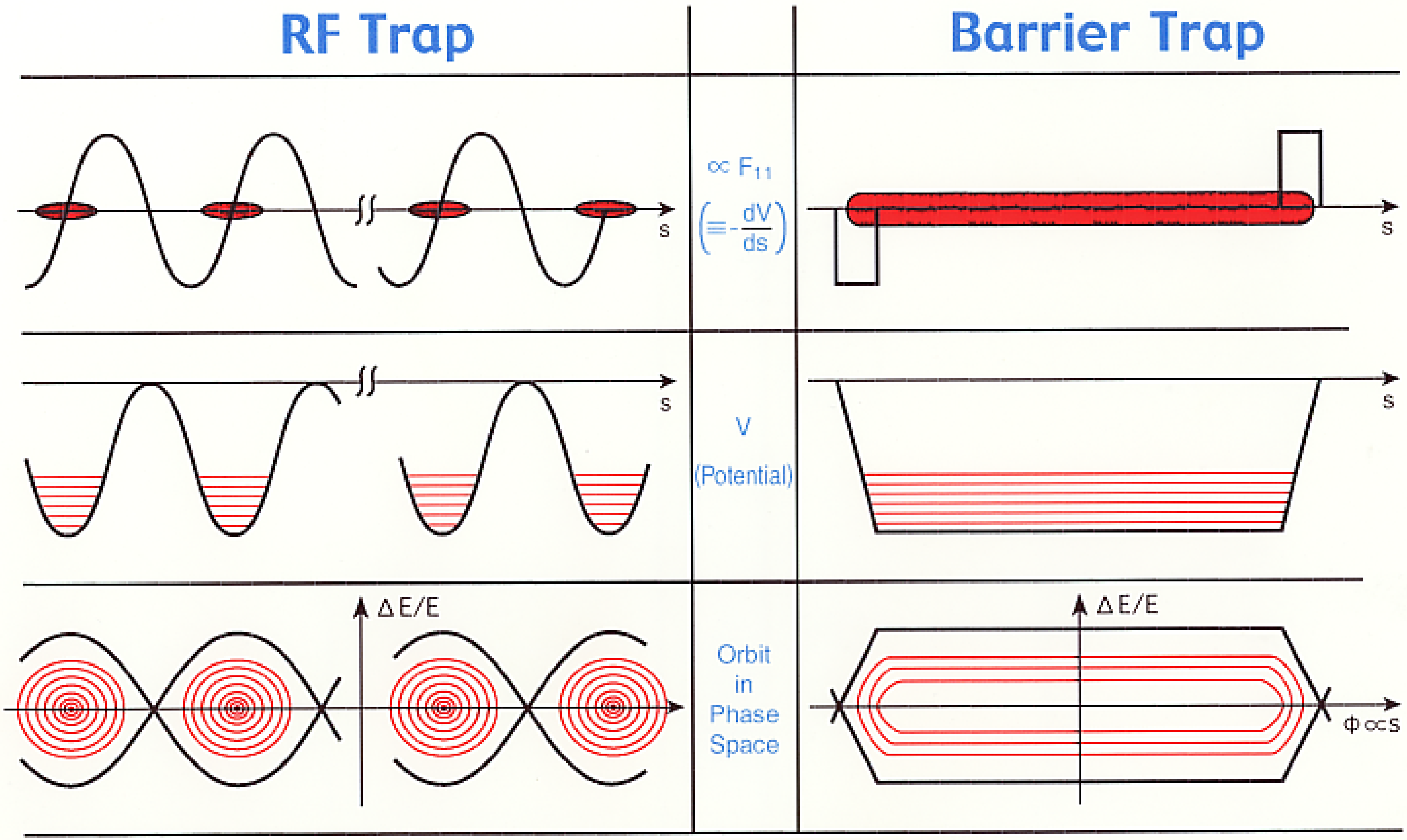


Dual Harmonic Bucket & Barrier Bucket

Daul Harmonic Bucket (h=1, 2)	Barrier Bucket
$V(t)=V_0\left\{\sin(\omega_{rf}t)-\delta\sin(2\omega_{rf}t+\theta)\right\}$ $\delta>0$	$V(t)=\begin{cases}-V_0 & t_1\le t\le t_2\\ 0 & t_2\le t\le t_3\\ V_0 & t_3\le t\le t_4\end{cases}$
	
	

#1

#2


RF Trap
Barrier Trap
∝ F11
(≡ - dV/ds)
V
(Potential)
Orbit
in
Phase
Space
s
s
s
s
ΔE/E
ΔE/E
φ ∝ s

3GeV-Booster@JHF

N=8x10^13

injection=330μsec

h=1

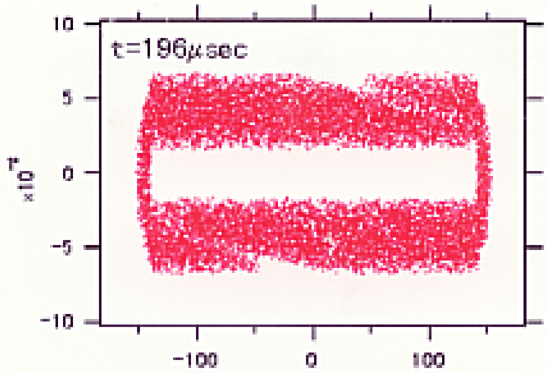
C0=313.5m

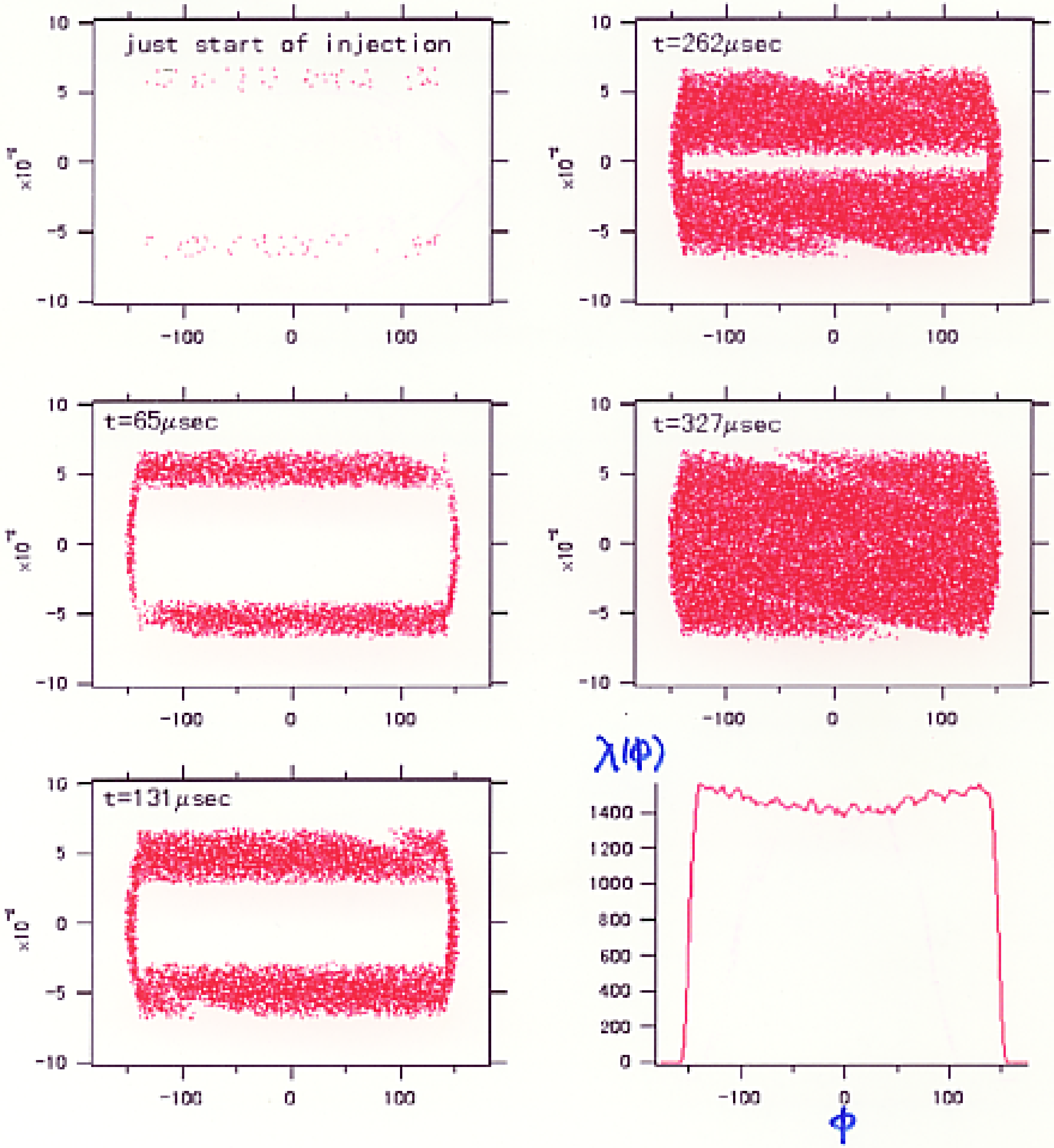
γt=8.77

b/a=1.8

V=200kV

Einj=400MeV

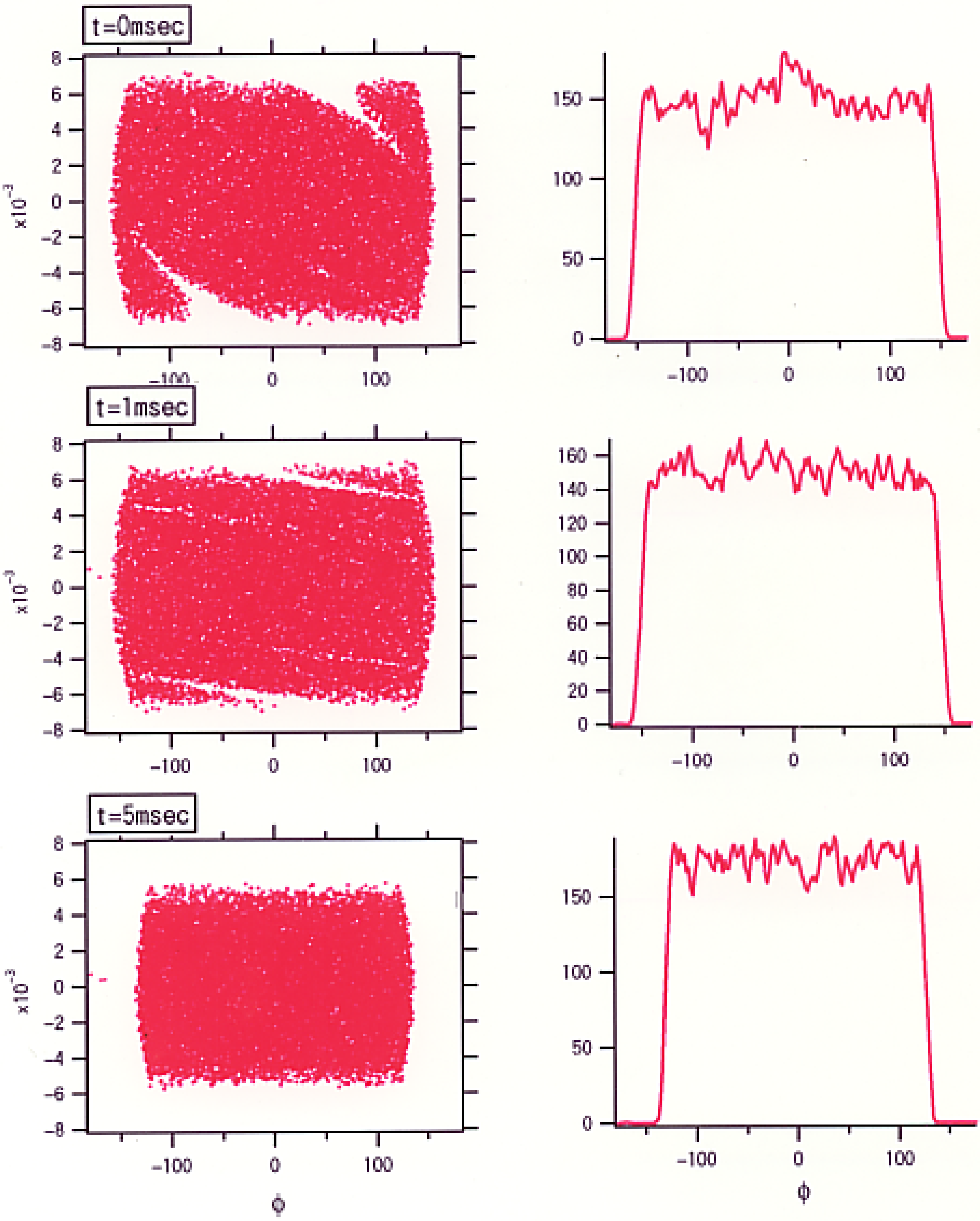


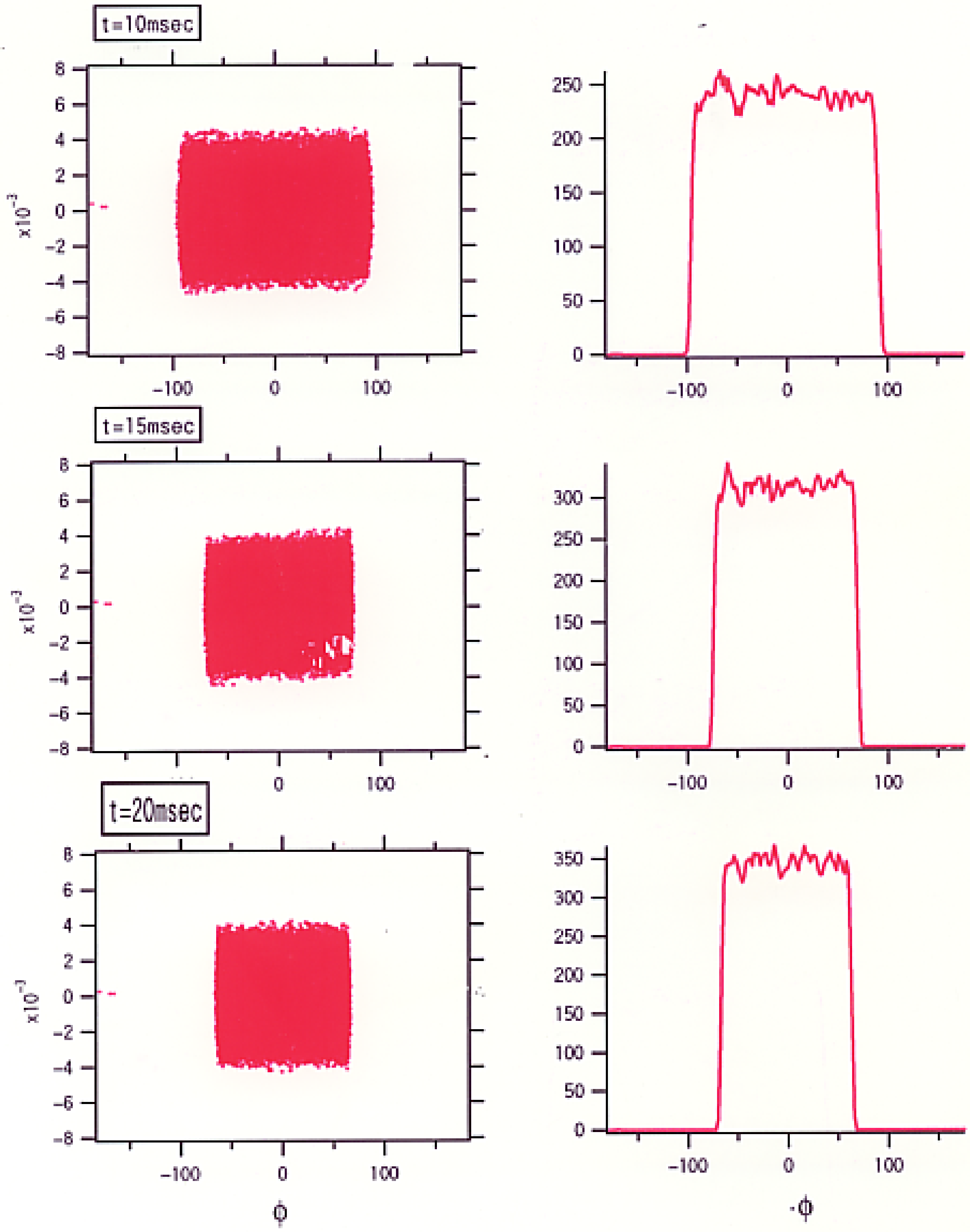


Bunching factor: $B_f = \frac{\left(\int \lambda(\phi)\,d\phi / 2\pi\right)}{\hat{\lambda}} = 0.76$

Incoherent Tune-shift: $\Delta\nu \propto \frac{N}{B_f} \le 0.25$ (Space-charge limit)

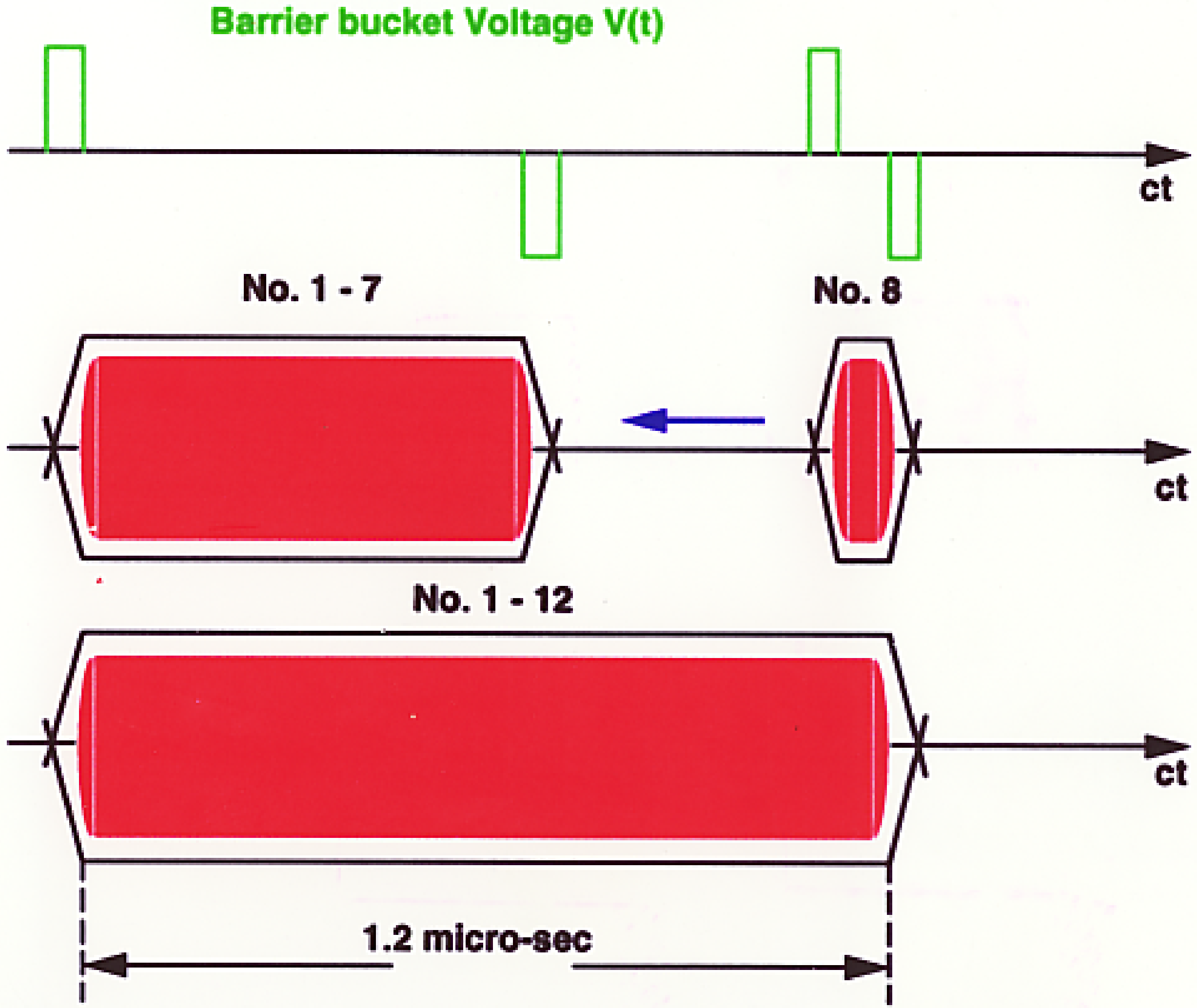
Stacking/Acceleration by a Barrier Bucket in the 3GeV Booster





t=10msec
t=15msec
t=20msec
x10^-3
8
6
4
2
0
-2
-4
-6
-8
-100
0
100
250
200
150
100
50
300
350
φ

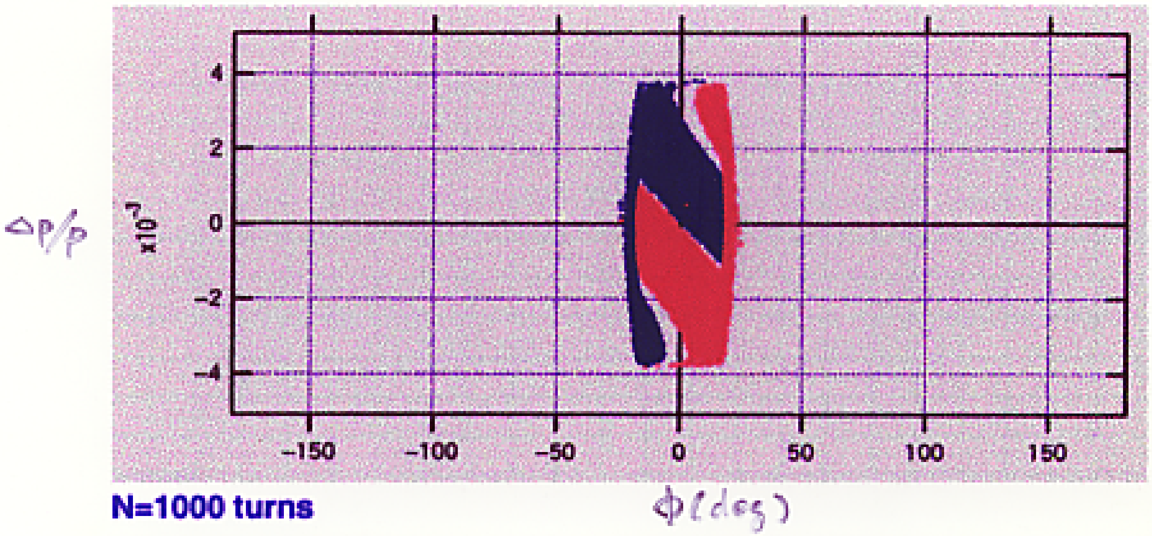
Multi-bunch Stacking



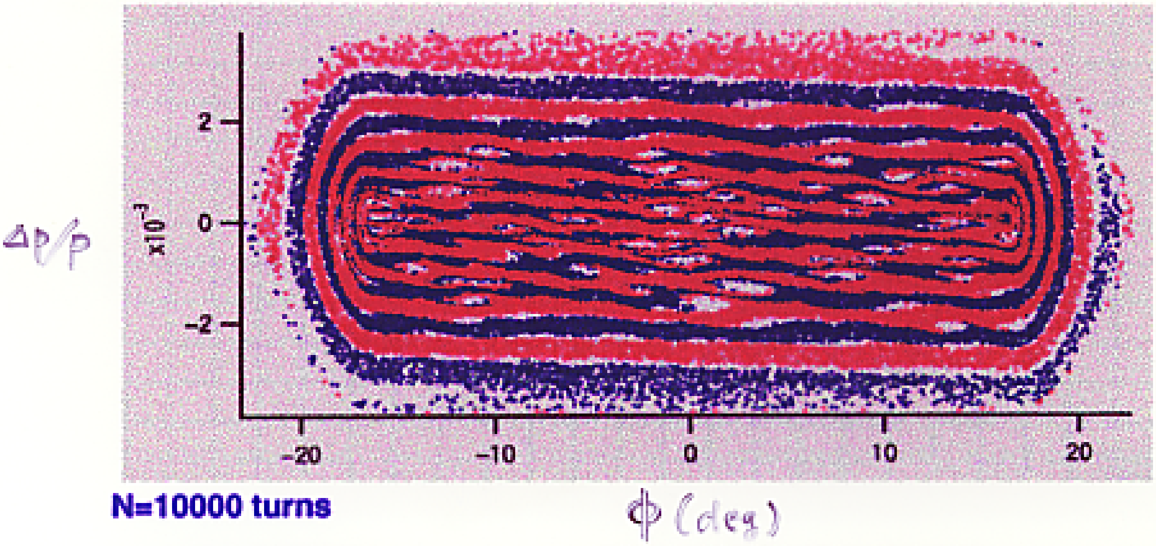
Key point: Many bunches can be stacked without increasing a local density.

Combining of two bunches

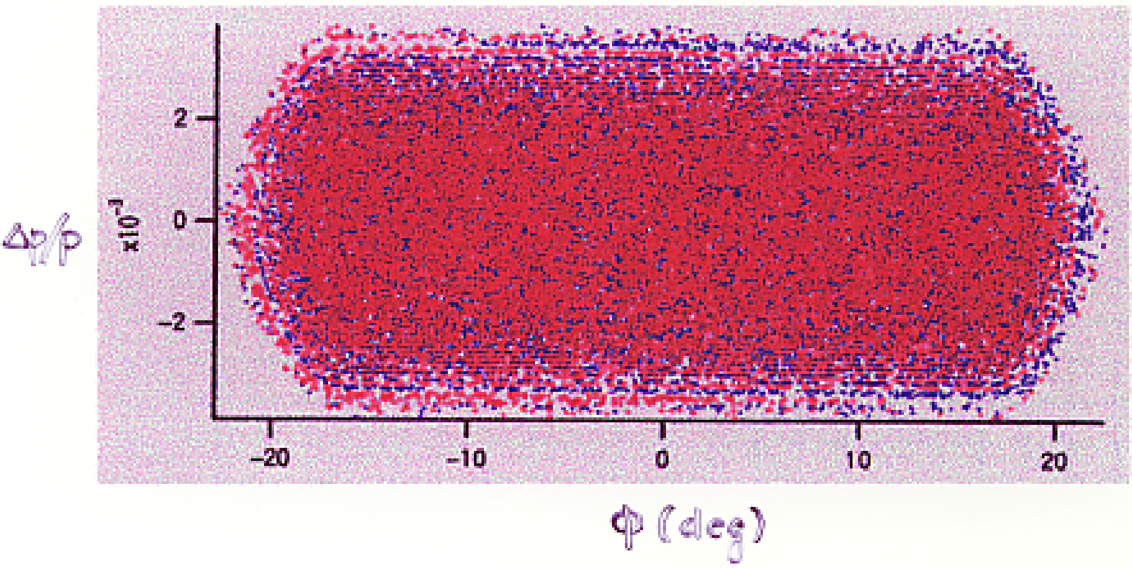
N=100 turns



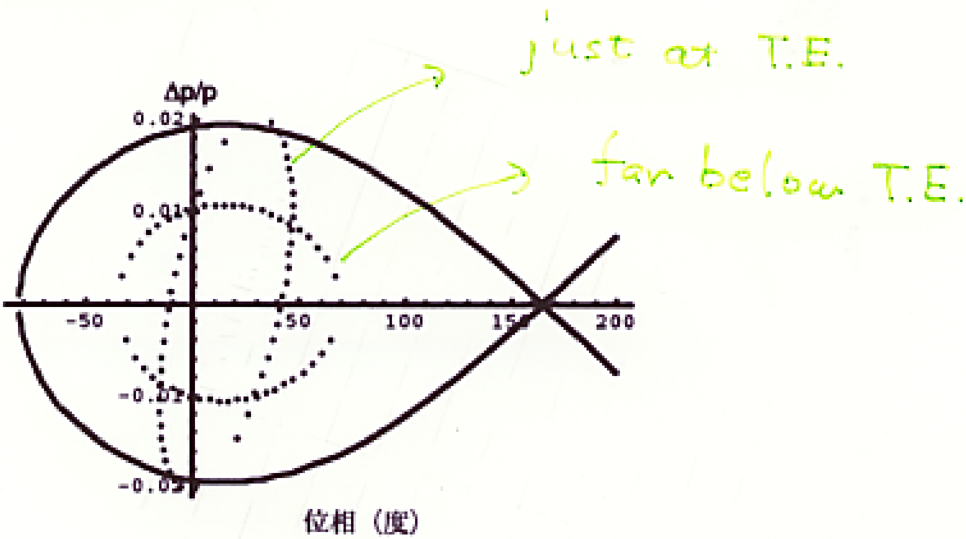
N=1000 turns



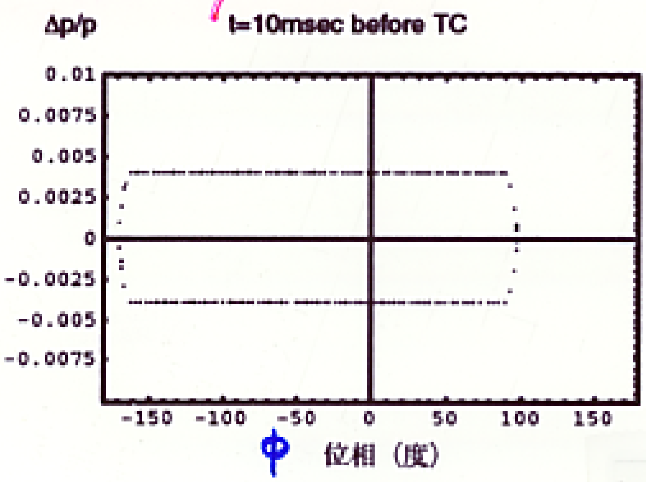
N=10000 turns

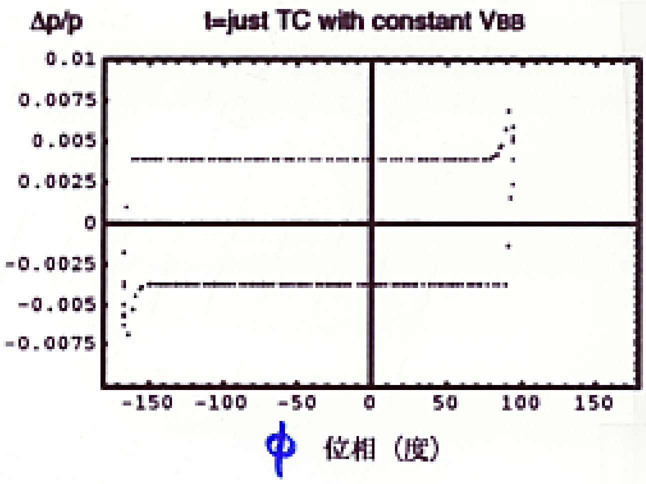


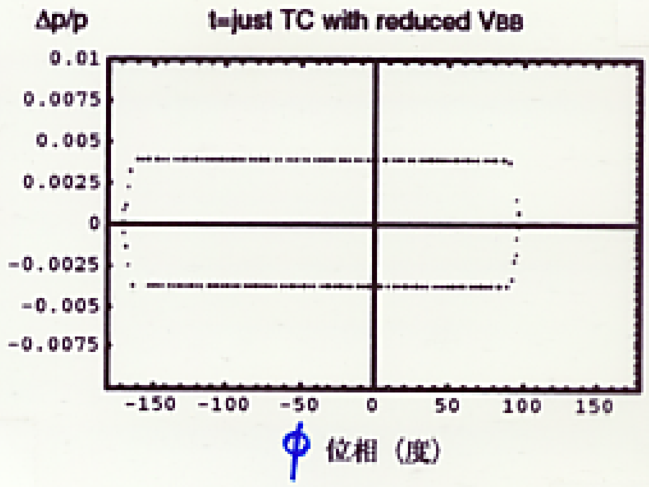
RF Synchrotron



Induction Synchrotron





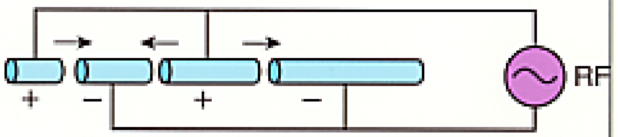


Transition Crossing

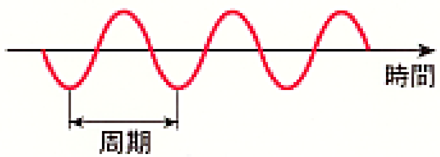
2　現代粒子加速器の依って立つ３大原理

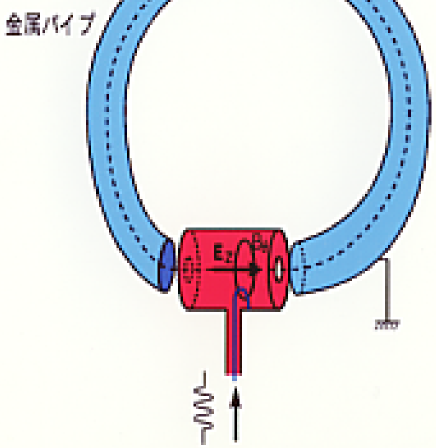
共鳴加速

1928 R.Wideroe



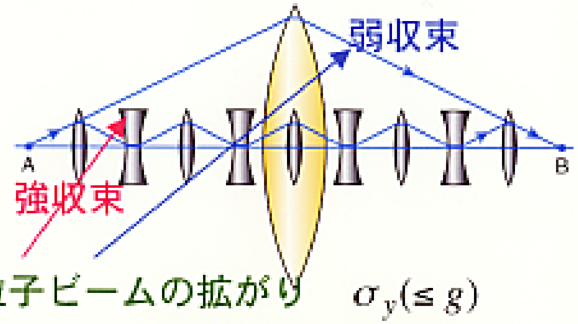
高周波（RF）の電圧波形

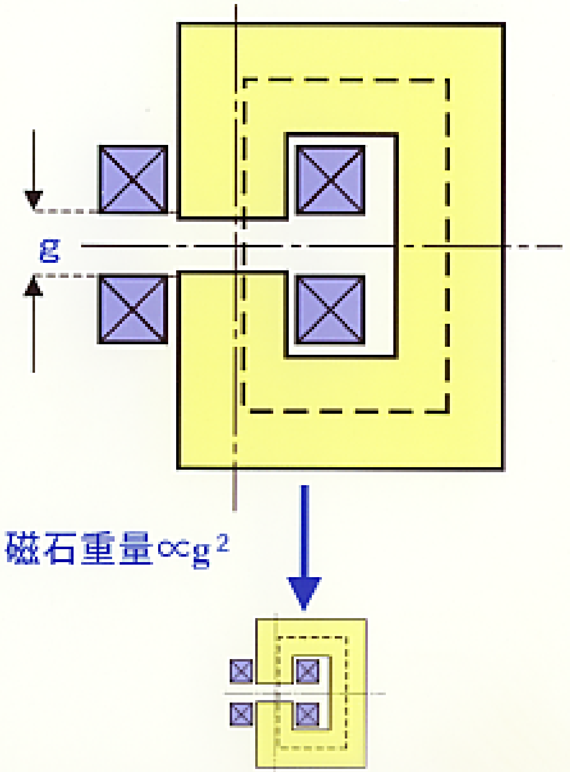




強収束

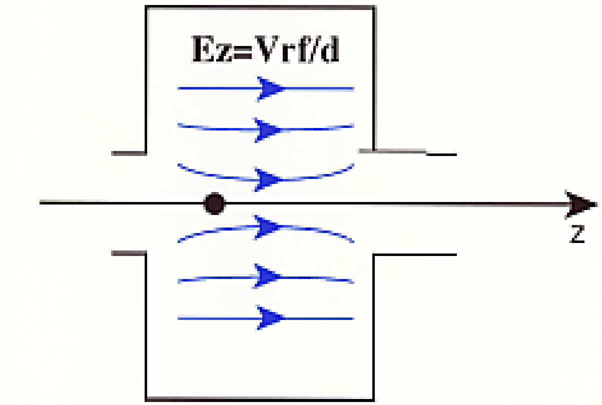
1952 E.D.Courant, M.S.Livingston
H.S.Snyder

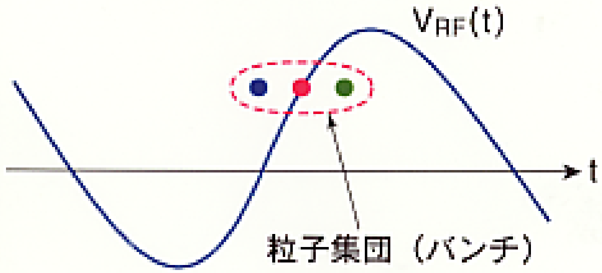


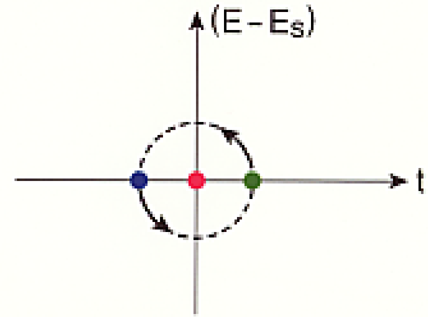


位相安定性

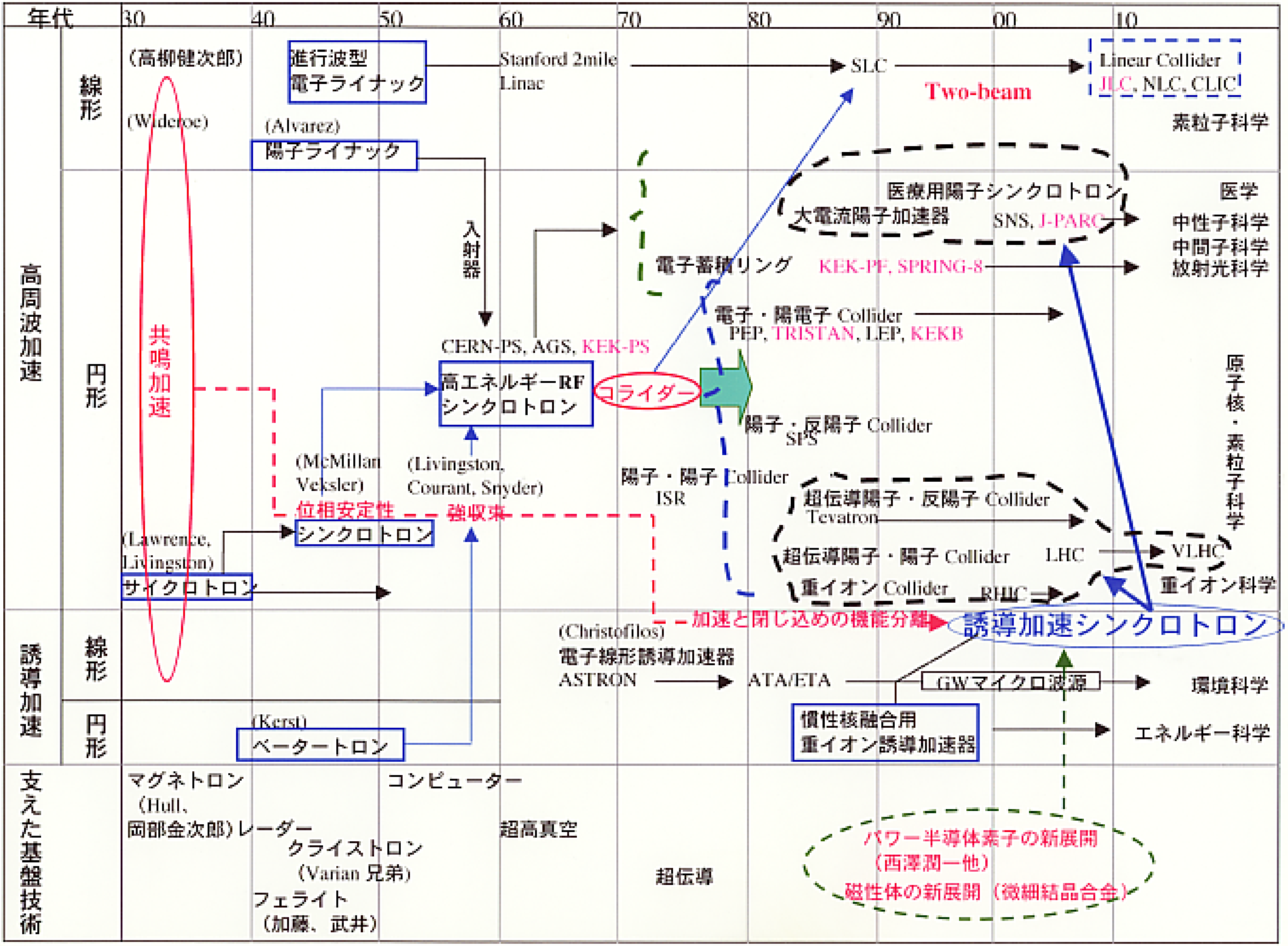
1945 E.M.McMillan, V.Veksler





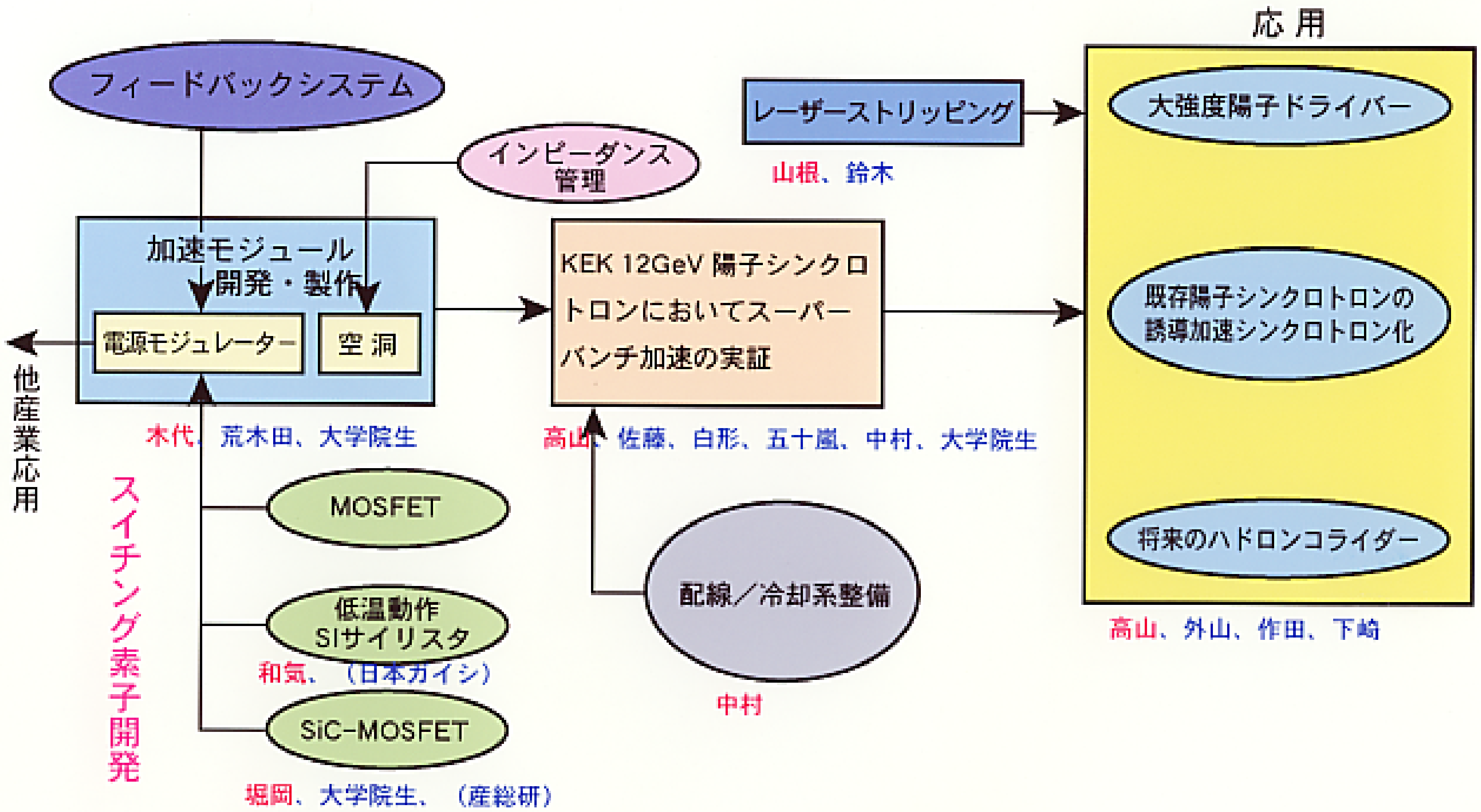


加速器の進化と誘導加速シンクロトロンの位置付け



5　研究計画のアウトラインと推進体制

高山（研究代表、全体統括）



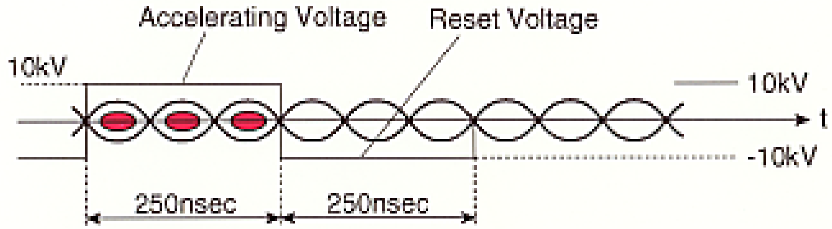
赤字：グループリーダー

研究計画実施スケジュール

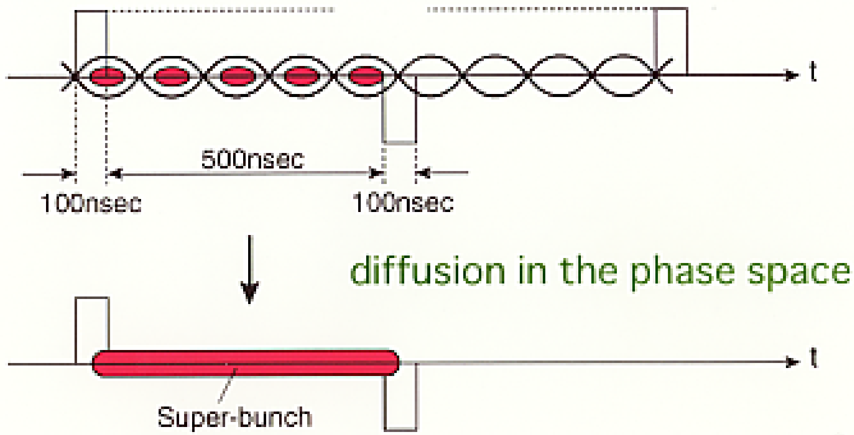
		平15 ('03)	平16 ('04)	平17 ('05)	平18 ('06)	平19 ('07)
A	加速モジュール（モジュレーター、加速空洞）の開発と製作 A-1 MOSFET搭載 A-2 SI-サイリスタ搭載 A-3 SiC-MOSFET搭載	A-1＋加速空洞 4セット製作 A-2 開発試験 A-3 開発試験	A-1＋加速空洞 12セット製作	A-1,A-2, or A-3+加速空洞（加速用２セット＋閉じこめ用１０セット）製作	A-1,A-2, or A-3+加速空洞（閉じこめ用）６セット製作	A-1,A-2, or A-3+加速空洞（閉じこめ用）６セット製作
B	段階的スーパーバンチ加速実証試験	ステップ 1 世界初誘導加速試験 加速電圧 V=10kV/ターン	ステップ 2 疑似スーパーバンチハンドリング試験 加速電圧25kV/ターン		ステップ 3 スーパーバンチ加速試験	加速電圧 22.5kV 閉じ込め電圧55kV
C	負イオンレーザーストリッピング法の実証	157nm F2ガスレーザーザーを用いたストリッピング装置の一部製作	BNL 200MeVライナックビームを用いての実験 紫外域ファブリーペロー共振器の開発	380nmファブリーペロー共振器の一部製作		米国 SNS での実証試験
D	スーパーバンチのビーム物理とコライダー用検出器の評価	集団不安定の理論研究 ビーム・ビーム相互作用の系統的研究 検出器の問題点の評価 可能な物理の探査	ビームハロー生成機構の研究	傾斜衝突方式対応インサーション Lattice の設計		
	その他				一部加速ユニットをFNALに持ち込み実証試験	一部加速ユニットをCERN-SPSに持ち込み実証試験
	KEK-PS 運転状況	営業運転		テストビーム供給運転		将来構想に依存する

Staged Scenario of the POP Experiment

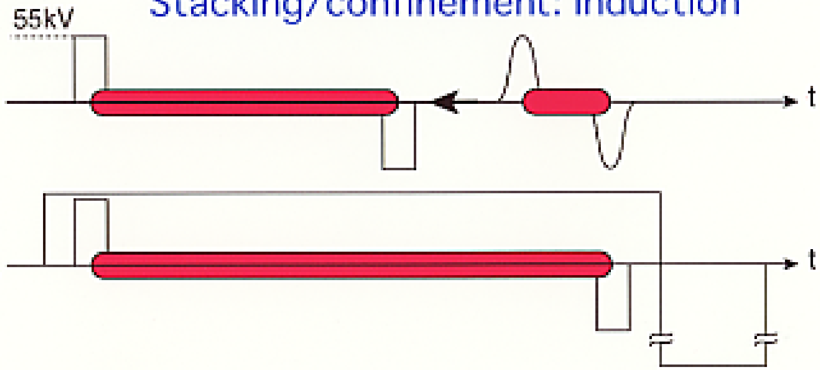
Step 1 Acceleration: Induction (500MeV -> 12GeV)
Confinement: RF



Step 2 Super-bunch generation exercise at 500MeV



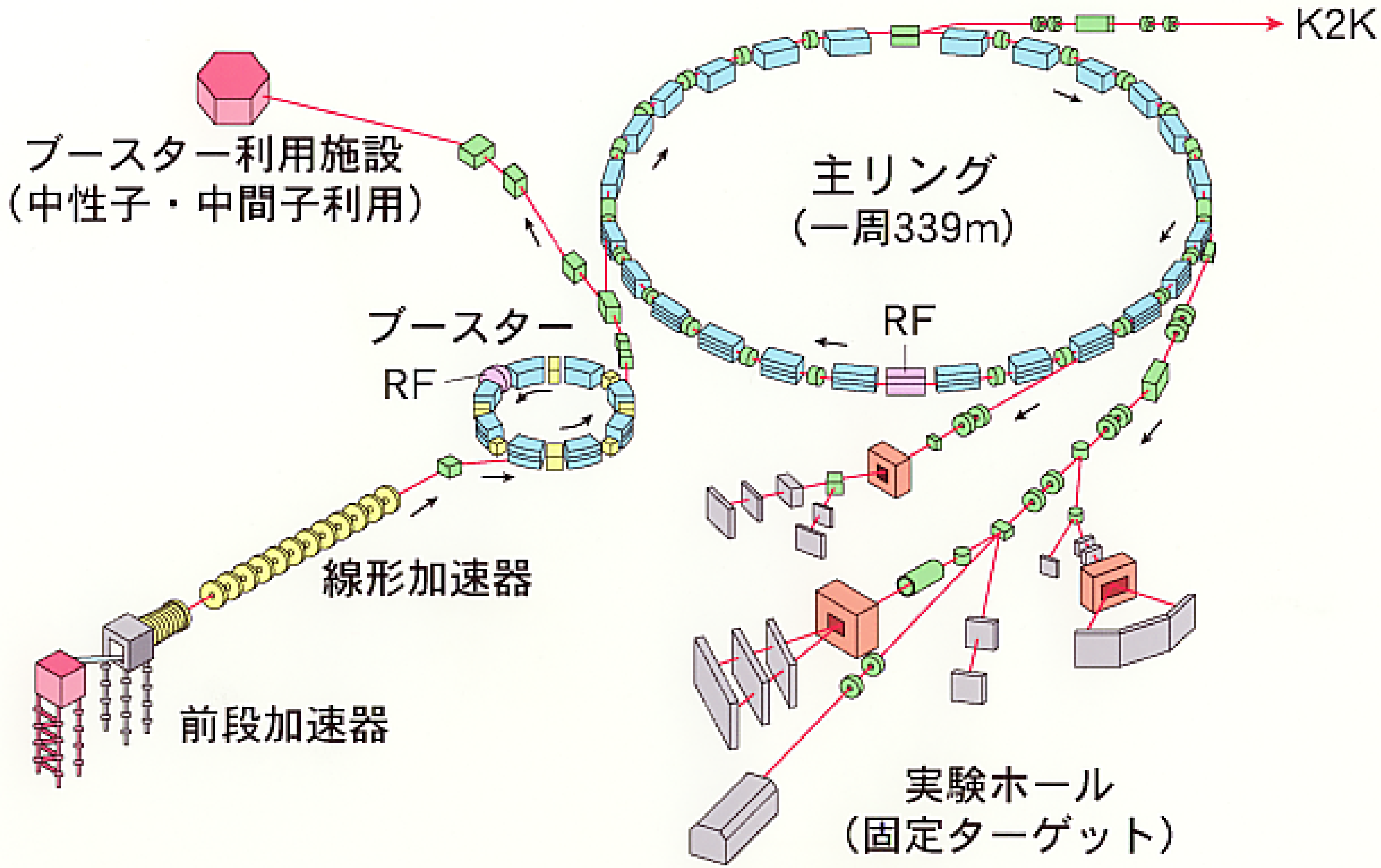
Step 3 Acceleration: Induction
(500MeV ->12GeV)
Stacking/confinement: Induction



Cost: 4.5M US$ or
500M Japanese Yen
(学術創成研究助成 nominated)

Time duration: 2003 -> 2007

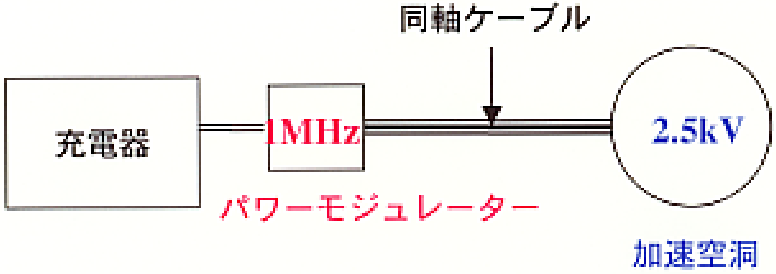
KEK 12GeV PS



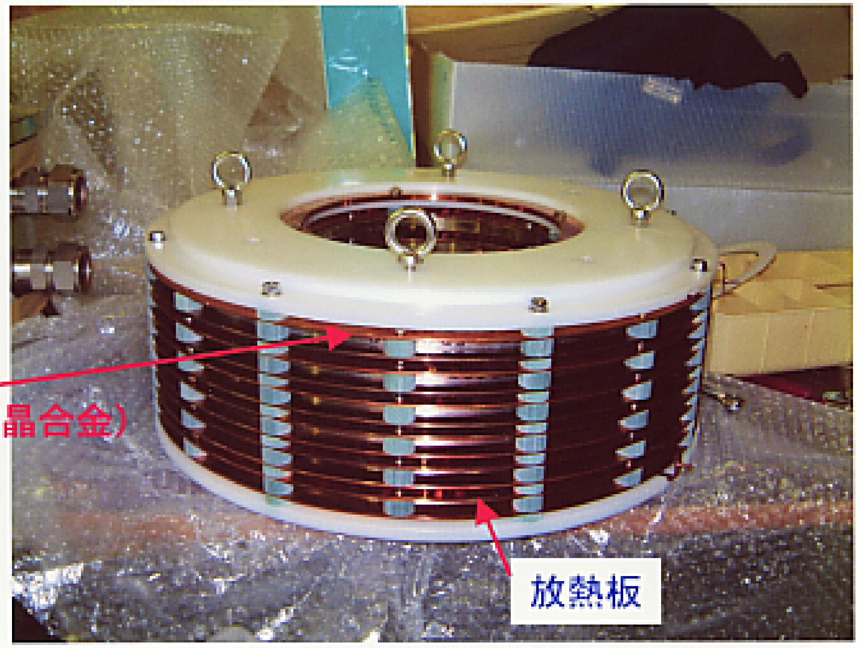
K2K
ブースター利用施設
（中性子・中間子利用）
主リング
（一周339m）
RF
ブースター
RF
線形加速器
前段加速器
実験ホール
（固定ターゲット）

4　研究の現状（１）：誘導加速装置の R&D

必要なデバイス



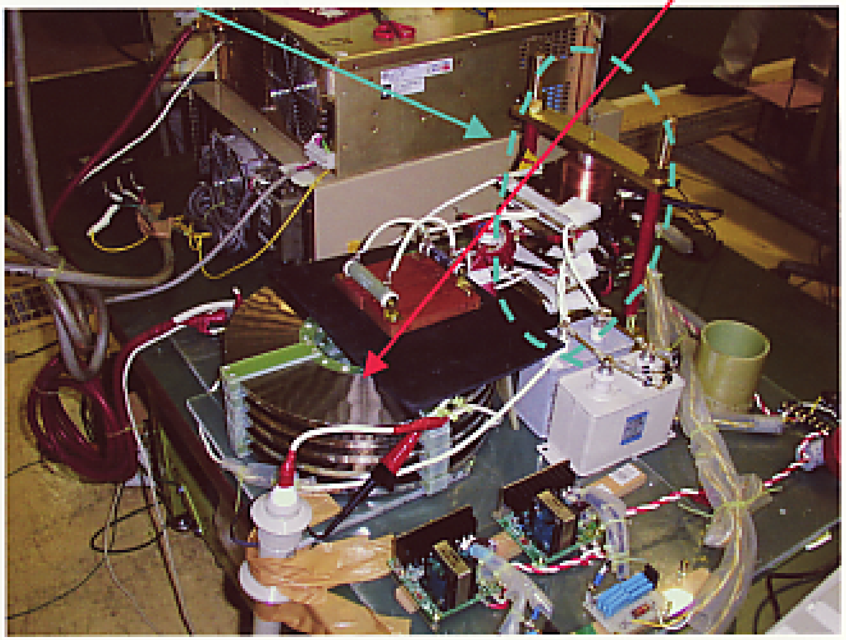
加速空洞用磁性体スタック

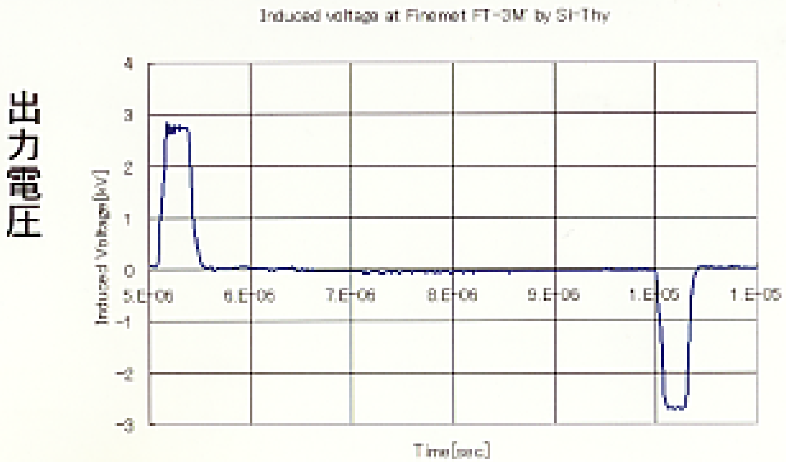


磁性体（微細結晶合金）

実 負荷試験

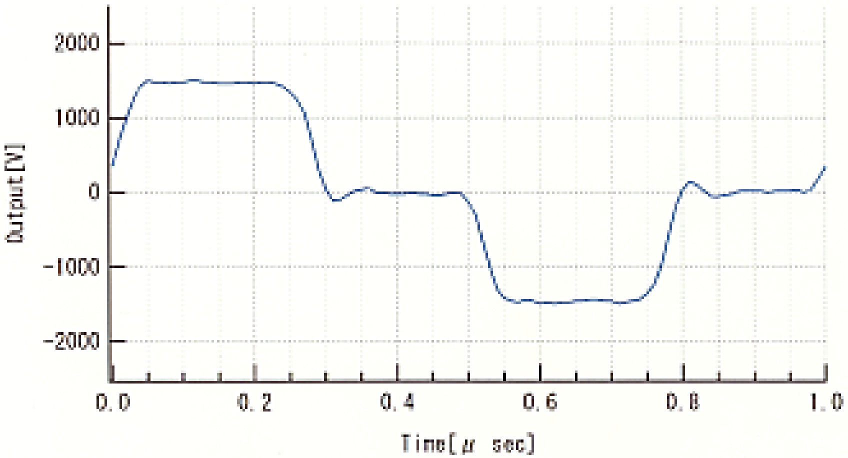
繰り返し：200 kHz
出力：3 kV
スイッチング素子：SIサイリスタ



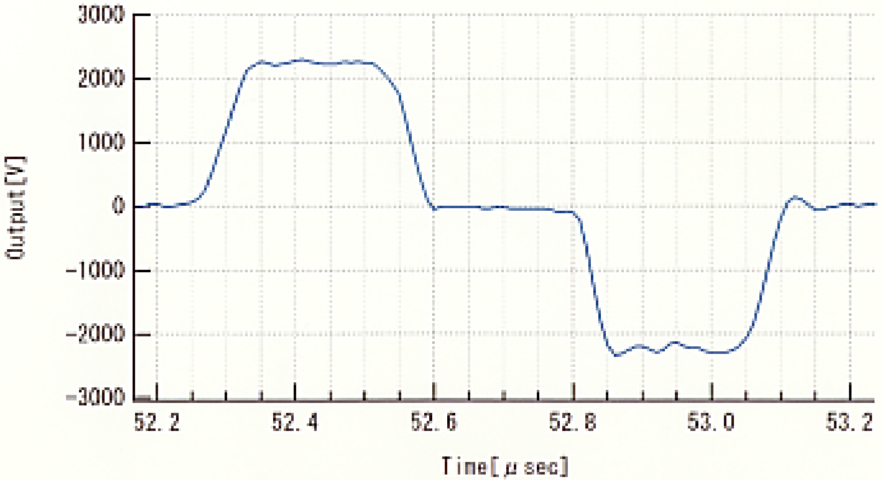


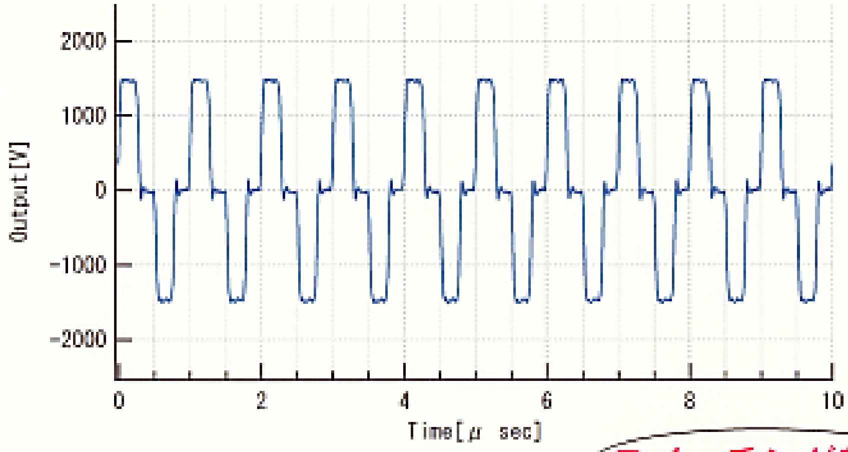
４　研究の現状（２）
450オーム抵抗負荷試験

繰り返し：1 MHz(CW)
出力：1.5 kV



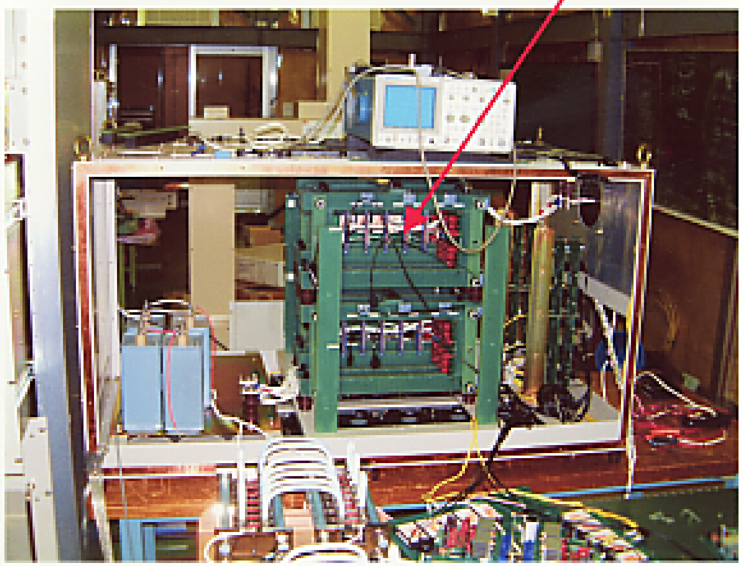
繰り返し：1 MHz（バースト）
出力：2.2 kV



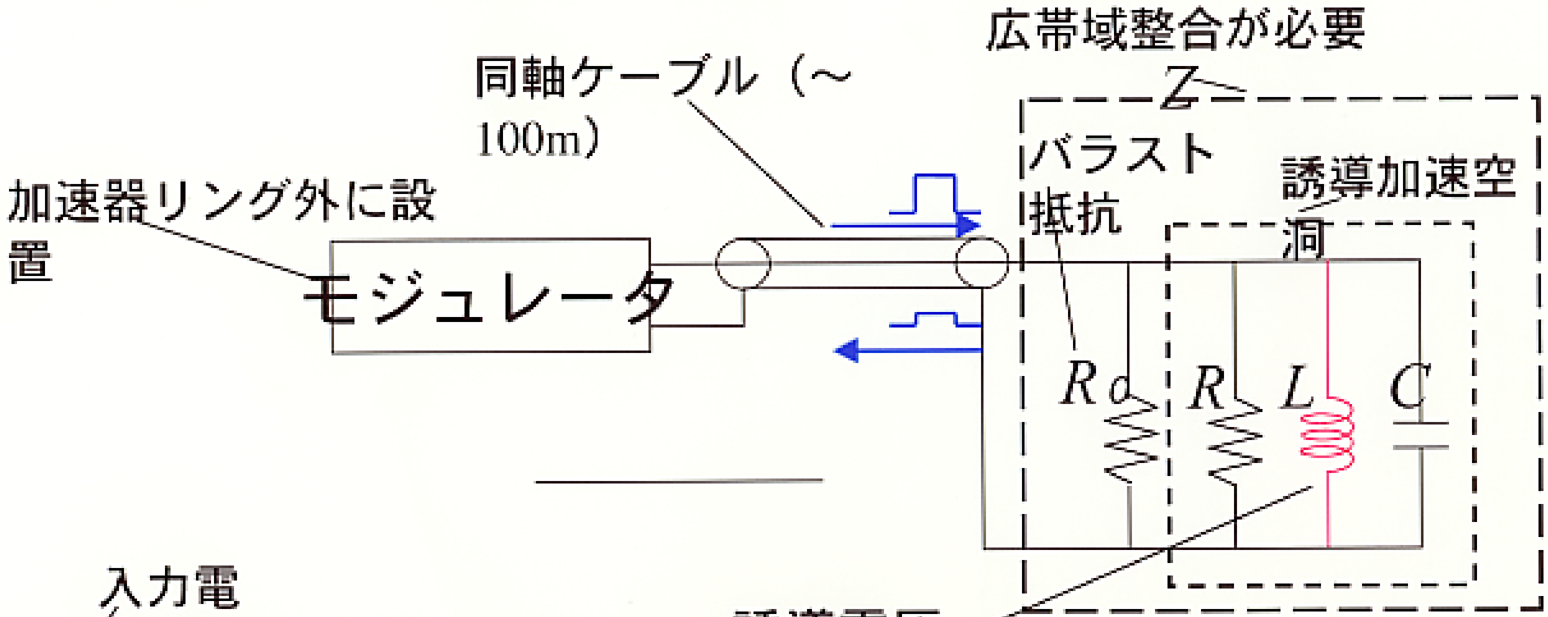


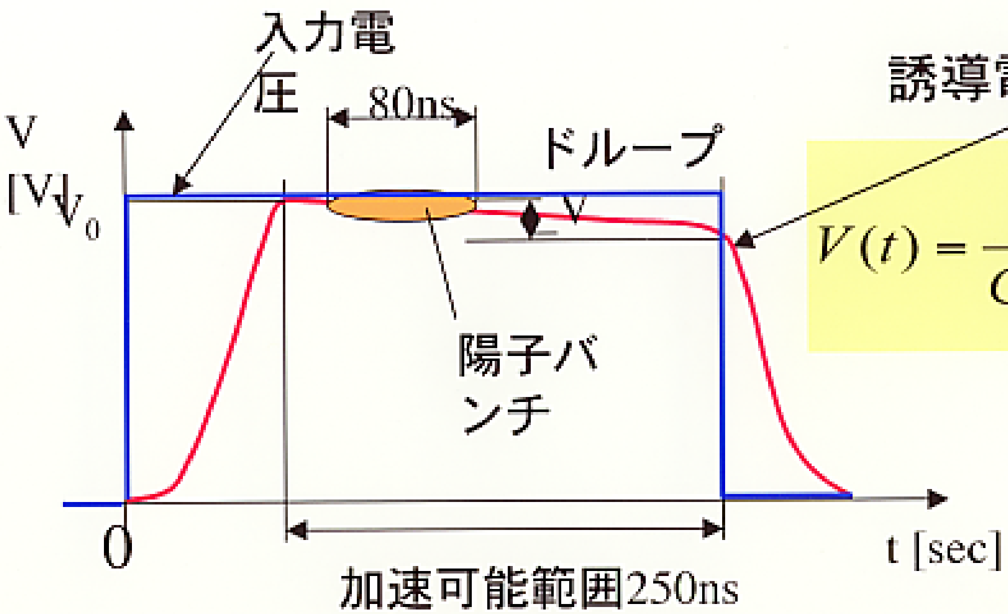
スイッチング基板

モジュレーター
スイッチング素子：MOSFET



等価回路モデルと解析的出力波形





$$V(t)=\frac{V_0}{CR_0}\left[\frac{\omega}{\sqrt{\xi^2-1}}e^{-\xi\omega t}\sinh(\sqrt{\xi^2-1}\omega t)\right]$$

$$\xi=\frac{1}{2}\sqrt{\frac{L}{C}}\left(\frac{1}{R}+\frac{1}{R_0}\right)$$

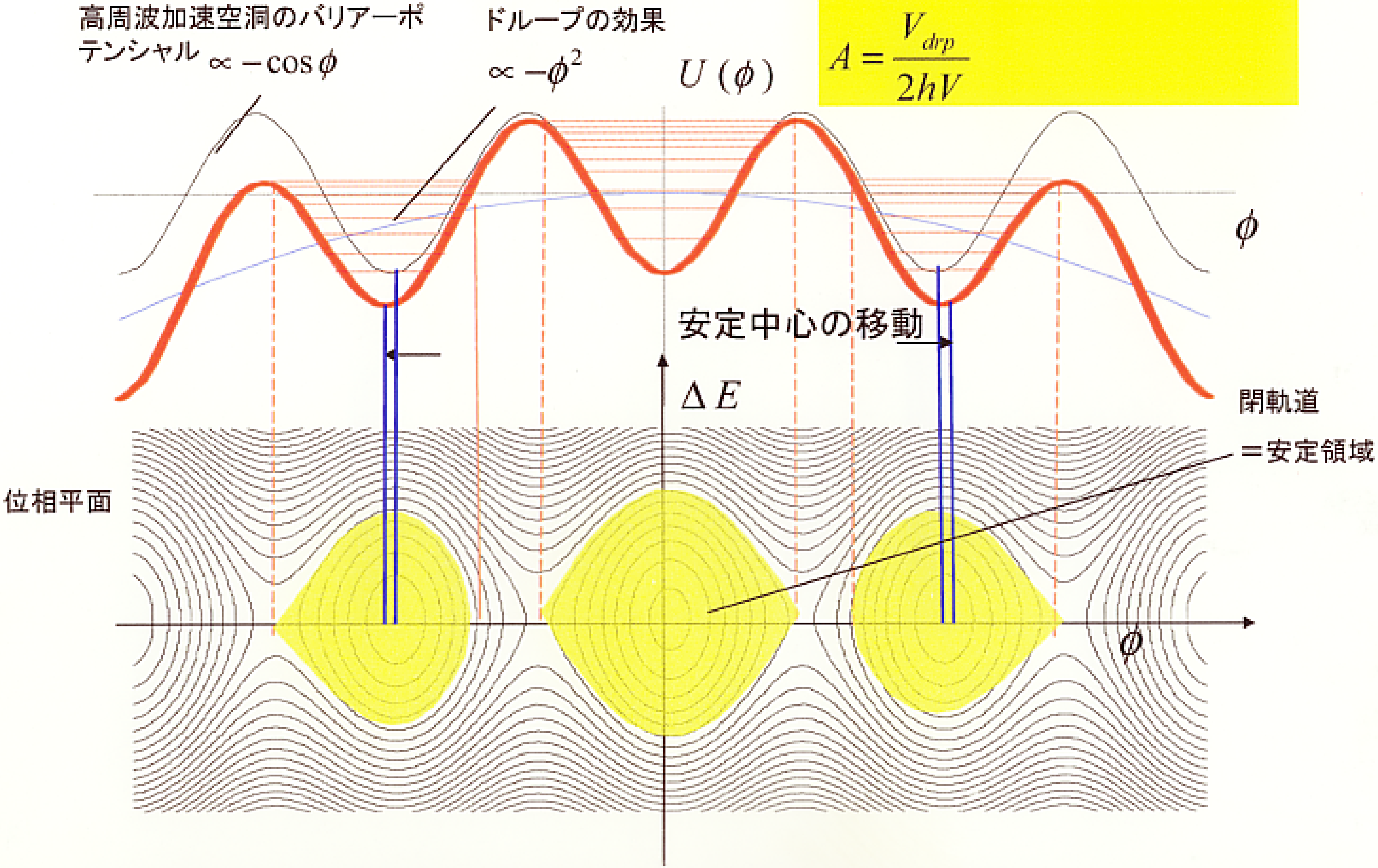
$$\omega=\frac{1}{\sqrt{LC}}$$

by 鳥飼幸太

ポテンシャルと位相安定性

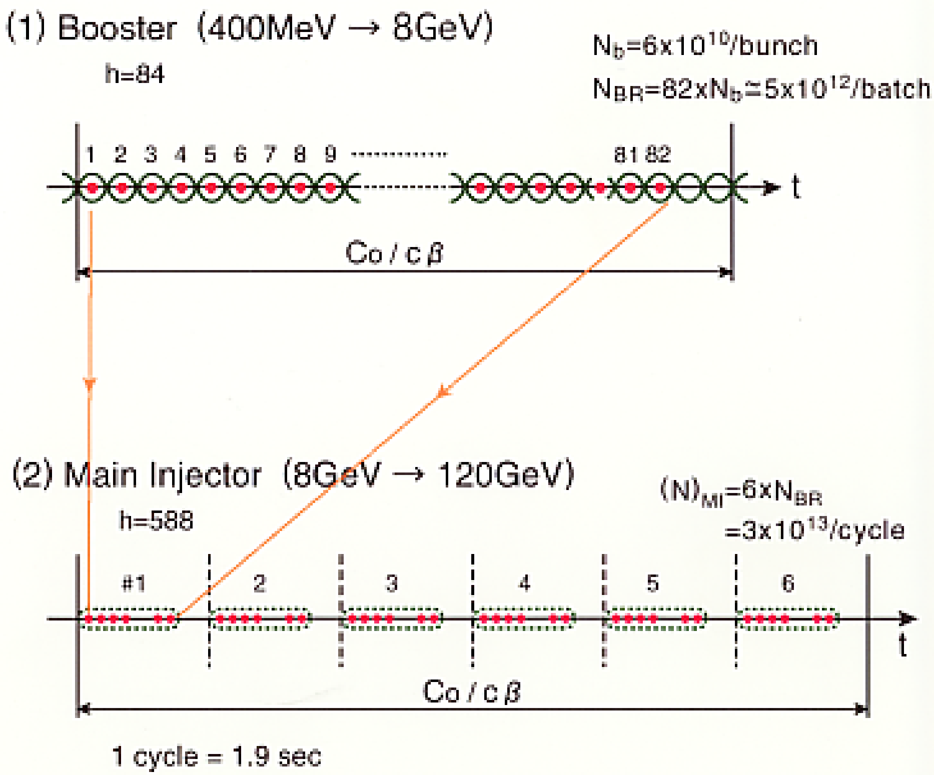
$$U(\phi) = -\frac{heV}{2\pi}(\cos\phi + A\phi^2)$$

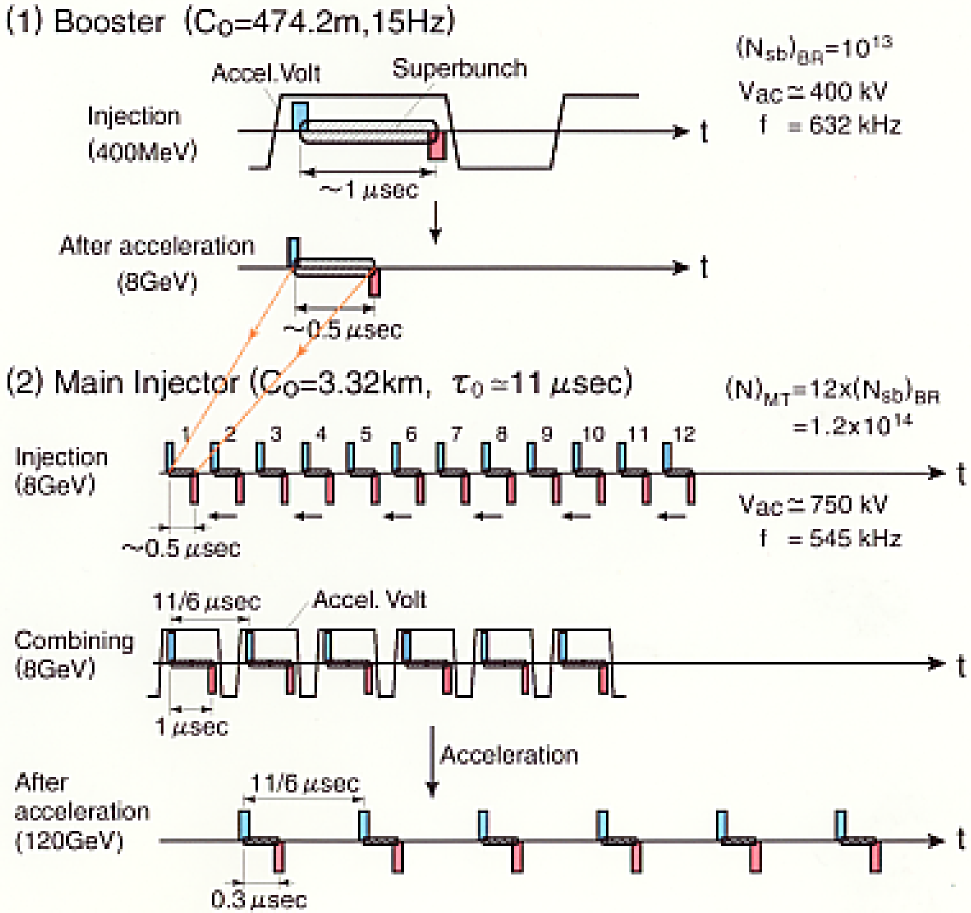
$$A = \frac{V_{drp}}{2hV}$$



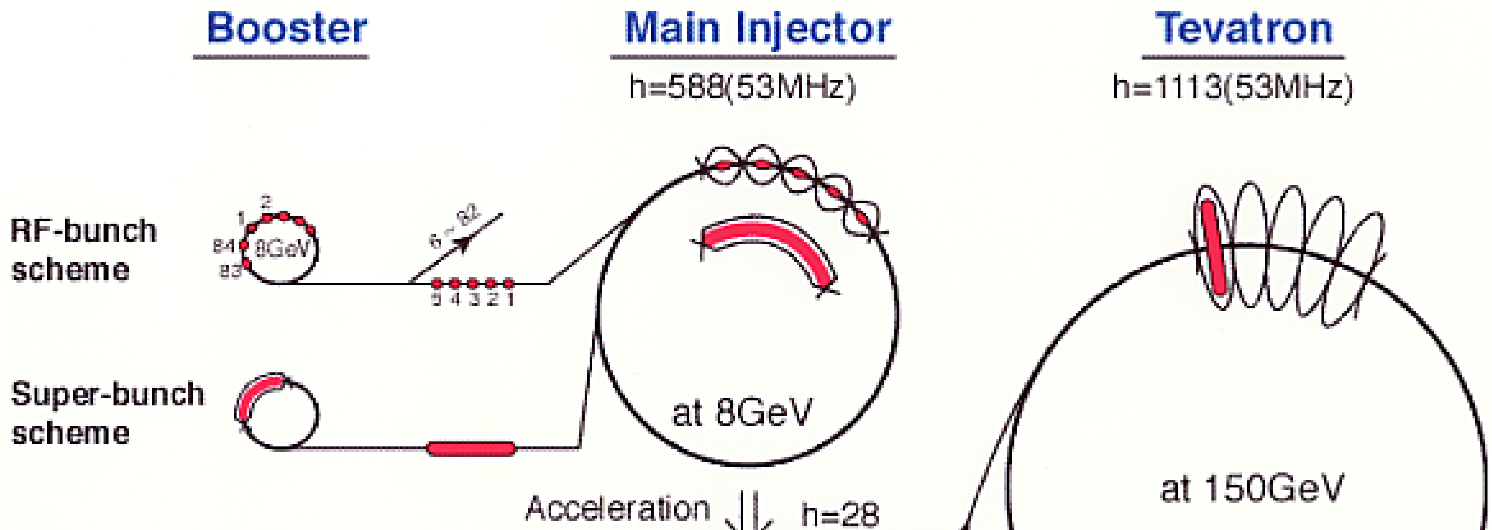
Proton Beam for MINOS Experiment

RF - bunch scheme	***Superbunch scheme***



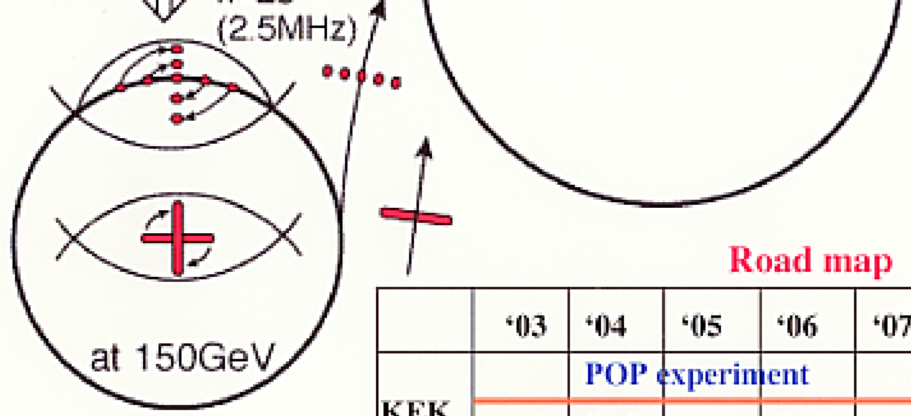


Proton Beam Formation in the Collider Operation Mode



Staging:

1. Chopped Beam Injection
   + Dual Harmonic Bucket Acceleration
2. Chopped Beam Injection
   + Dual Harmonic Bucket Trap
   + Induction Acceleration
3. Chopped Beam Injection
   + Short-pulse Induction Barrier Bucket Trap
   + Induction Acceleration

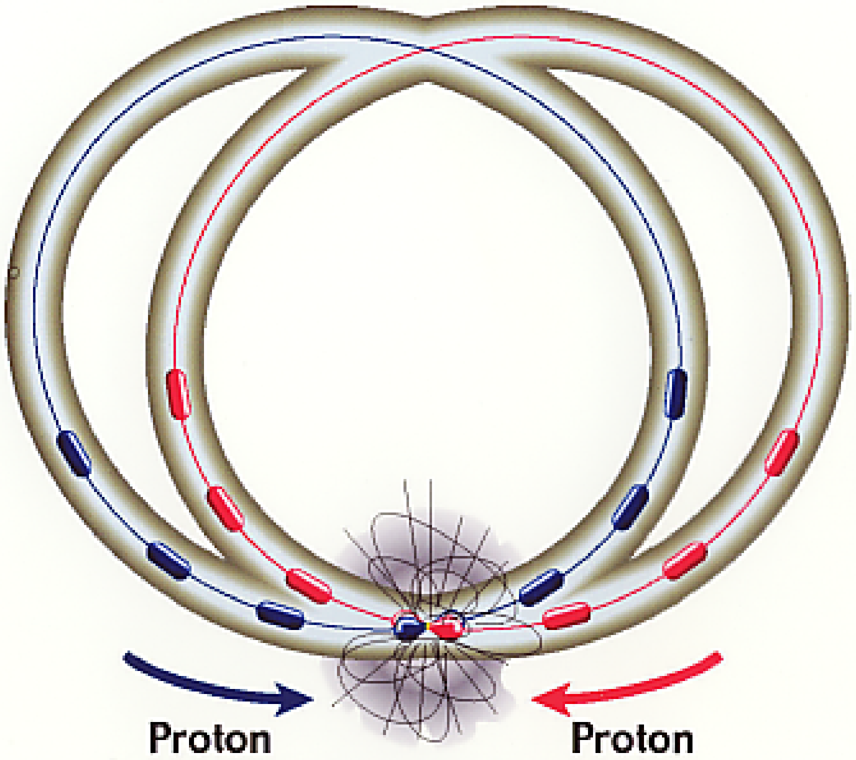


Road map

	'03	'04	'05	'06	'07	'08	beyond
KEK	POP experiment →; 1st →	2nd →		3rd →			LHC upgrade /VLHC
FNAL		Assemble →		Install/test in Main Injector →	Tevatron Run →		VLHC

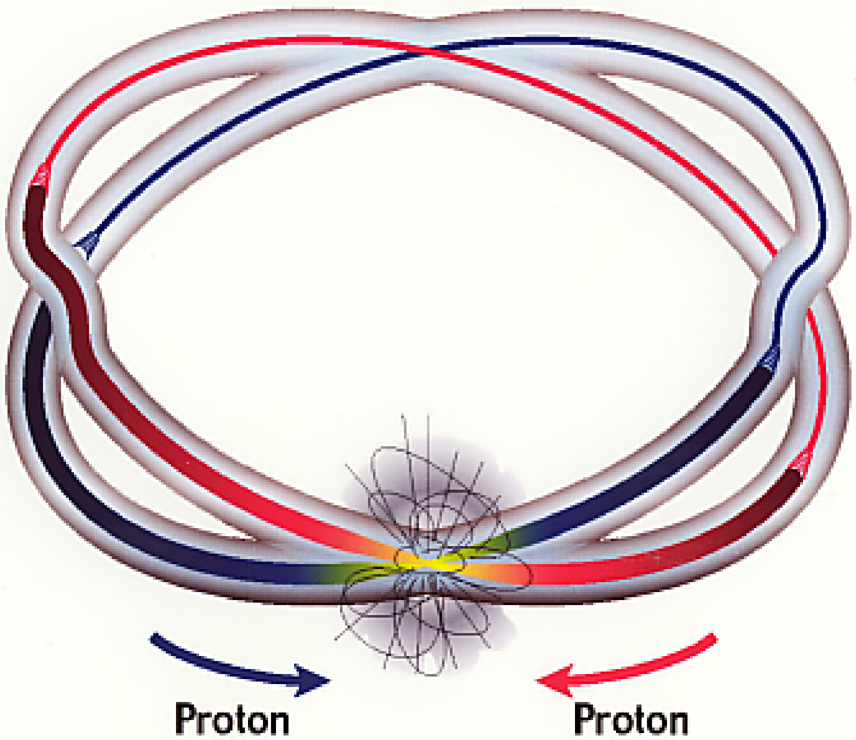
What is a SHC?

RF-bunch Hadron Collider



(Conventional Type)

Super-bunch Hadron Collider



(Novel Type)

K.Takayama, J.Kishiro, M.Sakuda, Y.Shimosaki, M.Wake
Phys. Rev. Lett. 88, 144801 (2002).

Milestone toward Super-bunch Hadron Colliders

Date	Authors or Institute	Pub. or Presentation	Remarks
Early 70's	CERN		Demonstration of the first continuous p-p beam collider (ISR)
1973	E.Keil	*Nucl. Inst. Meth.* 113, 333 (1973)	Luminosity, beam-beam tune-shift calculation for coasting beam collision
1983, March	J.Griffin et al.	PAC1983	Proposal of RF barrier bucket
1999, July	K.Takayama and J.Kishiro	νFACT'99 *Nucl. Inst. Meth.* 451, 304 (2000)	Concept of Induction Synchrotron
2001, March	K.Takayama et al.	KEK Preprint 2000-147 (2001)	First proposal of SHC concept
2001, June - July	R.Yamada, Super-bunch sub working-group	PAC2001 Snowmass 2001	Proposal of VLHC schemes with Super-bunch option Beam physics
2002, April	K.Takayama, J.Kishiro, M.Sakuda, Y.Shimosaki, and K.Wake	*Phys.Rev. Letts* 88, 144801 (2002)	Concept and Beam physics of SHC (Luminosity, tune-spread, inclined crossing)
2002, June	F.Zimmermann	EPAC2002, in Proc., 25 (2002)	e-p Instability in Super-bunch option
2002, October	F.Ruggiero,R.Garoby, F.Zimmermann et al.	LHC Project Report	Feasibility study of Super-bunch option in LHC upgrade

ISR

ISR Parameter List

Max. total energy	E_{max}	28 GeV
Average radius	R	150 m
Intersection angle	α	15°
No of magnet periods	N	48
No of superperiods	S	4
No of intersections		8
Long s.s. length		16.8 m
Q value	Q	8.75
Max. horizontal β value	β_H max	41 m
Max. vertical β value	β_V max	51 m
Max. momentum compaction	α_p max	2.3 m
No of magnets per ring		132
Max. field	B_o	1.2 T
Bending radius	ρ	78.5 m
Profile parameter	n/ρ	3 m^{-1}
Gap height		0.1 m
Harmonic number	h	30
R.F. volts per turn	50 V to	20 kV
Design pressure		10^{-9} torr
Vac. chamber dimensions		16 x 5.2 cm^2

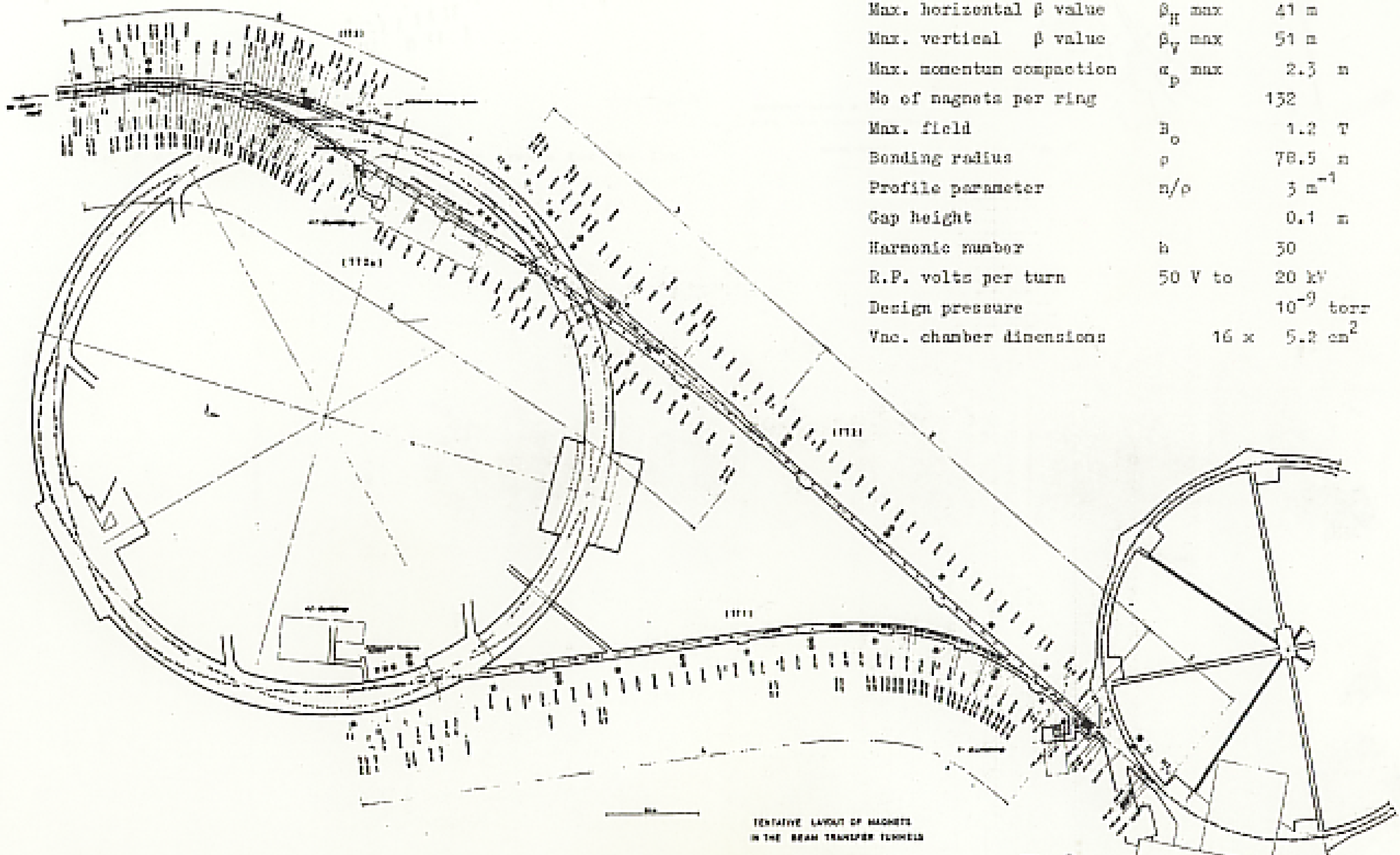
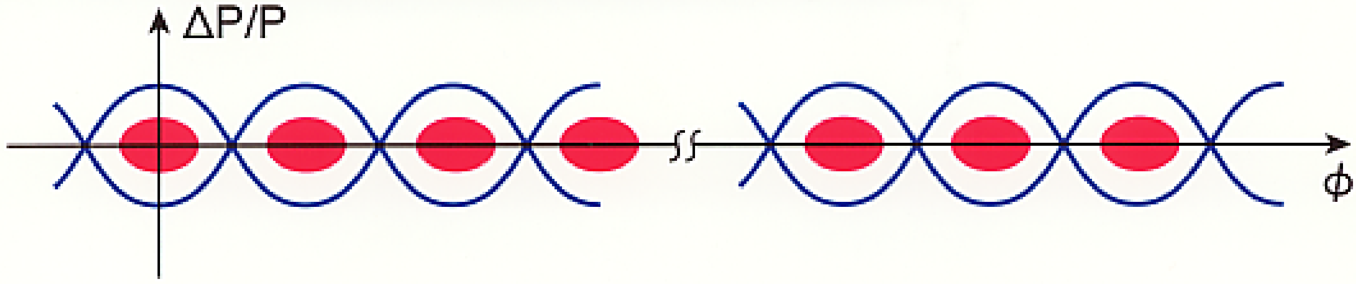


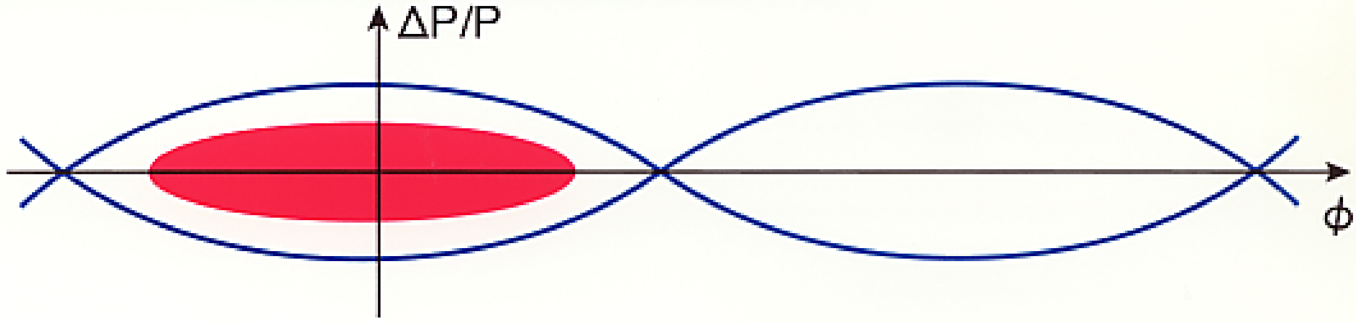
Fig. 2 : Lay-out of the beam transfer system for the ISR.

RF bunch & Super-bunch

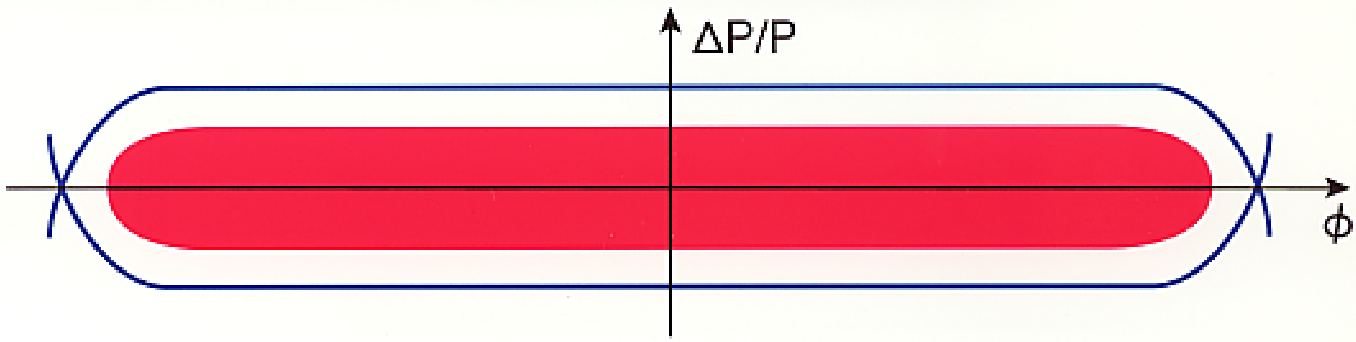
(1) Present higher harmonic RF bunch



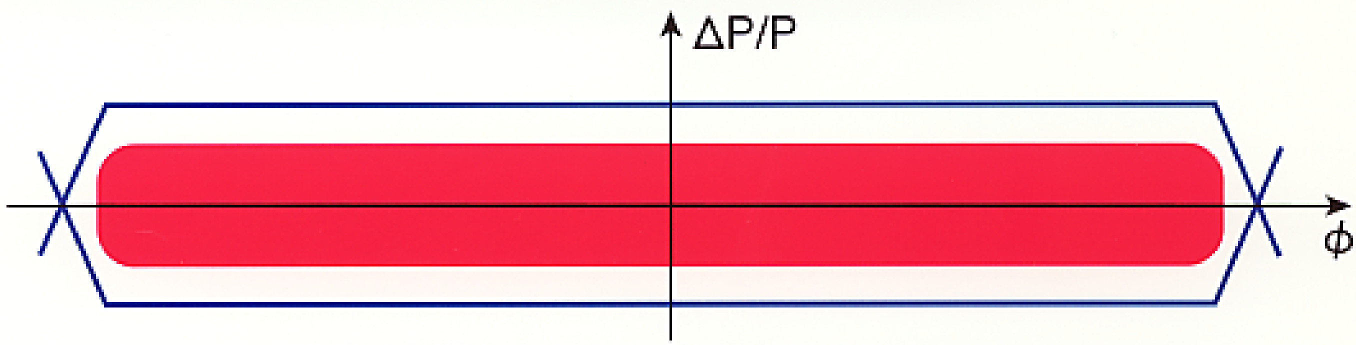
(2) Low harmonic RF Super-bunch



(3) Super-bunch in an RF barrier bucket



(4) Super-bunch in a Step-barrier bucket



Super-bunch

	Type of Super-bunch		
	Low harmonic RF bunch	Barrier bucket bunch	
		RF barrier	Step barrier
Required devices	low harmonic cavity and low freq. power source	● low Q cavity and multiple RFs or amplified pulse voltage	induction cavity
Characteristics			
Advantage	● well developed technology ● small RF voltage bucket height $\approx \left[\frac{V}{h}\right]^{1/2}$	● already demonstrated ● easy bunch formation	● easy bunch formation by only controlling a trigger timing ● uniform line density
Disadvantage	● limited available space in the phase space ● highest line density at the bunch center ● slow synch. osci.	● no acceleration ● slow synch. osci.	● not demonstarated yet ● slow synch. osci.
Remarks	● may need minor changes for bunch formation in the upstream ● merging process?	● good exercise for Step barrier beam handling	● needs modification for bunch-formation in the upstream accelerators

Limit or Overview of Conventional Hadron Colliders

Luminosity

$$L = F\frac{k_b N_b^2 f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}$$

k_b: number of bunches

N_b: number of protons / bunch

f_{rev}: revolution frequency

ε_n: normalized emittance

β^*: betafunction at the IP

F: reduction factor with crossing Φ

Beam physics limit

Space-charge limit in upstream accelerators:

$$\Delta\nu \propto N_b/\varepsilon_n \le 0.25$$

Beam-beam limit:

$$\xi = \frac{N_b r_0}{4\pi\varepsilon_n} \le 0.004 \text{ / IP (empirical)}$$

Cryogenetic limit

Synchrotron radiation limit:

$$P_{rad} \propto k_b N_b \le \text{a few watts / m}$$

Time resolution requirement from a detector

Bunch spacing limit: $d \ge 5m$

Beam occupation ratio

$$\kappa = \frac{\sqrt{2\pi}\sigma_s k_b}{C_0} \quad (\sigma_s\text{: rms bunch size})$$

$$= 2\% \text{ for LHC, } 1-3\% \text{ for VLHC}$$

Big Questions and recent activity on the SHC

- What is the luminosity of the SHC?
- What happens in the collision between super-bunches?
- What collision scheme is desired?
- What machine parameters are assumed?
- Various obstacles can be overcome or not?
- Are there further advantageous features with super-bunches?

- Preliminary results for case study at KEK and FNAL have been published in *Phy. Rev. Lett.* 88, 144801 (2002) and presented at Snowmass 2001 and at PAC2001.
- CERN has started their feasibility study as an upgrade plan of LHC since the last spring, where a low harmonic RF super-bunch is assumed. Big merits in introducing a super-bunch has been discussed at EPAC2002.
- Issues that require further studies have been discussed at RPIA2002, KEK.

Luminosity in the SHC

$$L_{SHC}(\Phi,\ell) = 4\frac{(k_{sb}\sigma_{sb})}{(k_b\sigma_s')}\frac{F_{SHC}(\Phi,\ell)}{\sigma_s' F_{CHC}(\Phi')}L_{CHC}(\Phi')$$

where k_{sb}, k_b: number of superbunches, RF bunches per beam

σ_{sb}: superbunch length (full)

$\sigma_s' = \sqrt{2\pi}\sigma_s$ (σ_s: rms RF bunch length)

Φ, Φ' : collision angle for SHC and CHC

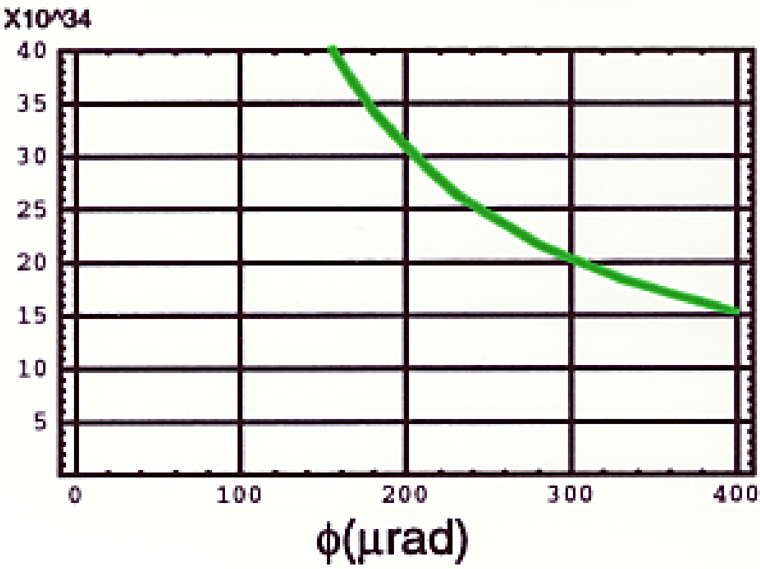
2ℓ: size of detector region

form factor:

$$F_{CHC}(\Phi') = 1/\sqrt{1+(\Phi'\sigma_s/2\sigma^*)^2}$$

$$F_{SHC}(\Phi,\ell) = \int_0^\ell \frac{\exp\left(-\frac{\gamma\Phi^2 s^2}{2\beta^*\varepsilon_n\left[1+(s/\beta^*)^2\right]}\right)}{\left[1+(s/\beta^*)^2\right]}ds$$

LHC-size SHC $(2\ell = 5m)$



Beam-beam tune shift in the SHC scheme

- **Beam-beam tune-shift can be analytically evaluated by manipulating the 0-th harmonics of the Fourier components in the beam-beam perturbation term.**
- **The tune-shift normalized by the tune-shift ξ in the head-on collision of the CHC scheme is given in the form,**

$$\frac{(\Delta\nu_x)_\Phi^{SHC}}{\xi} = \frac{8\beta^*\varepsilon_n}{\sigma_s'\gamma}\int_0^{l_{int}} \frac{1+s^2/(\beta^*)^2}{\Phi^2 s^2}\left[1-\exp\left(-\frac{\gamma\Phi^2 s^2}{2\varepsilon_n\beta^*\left(1+s^2/(\beta^*)^2\right)}\right)\right]ds \tag{1}$$

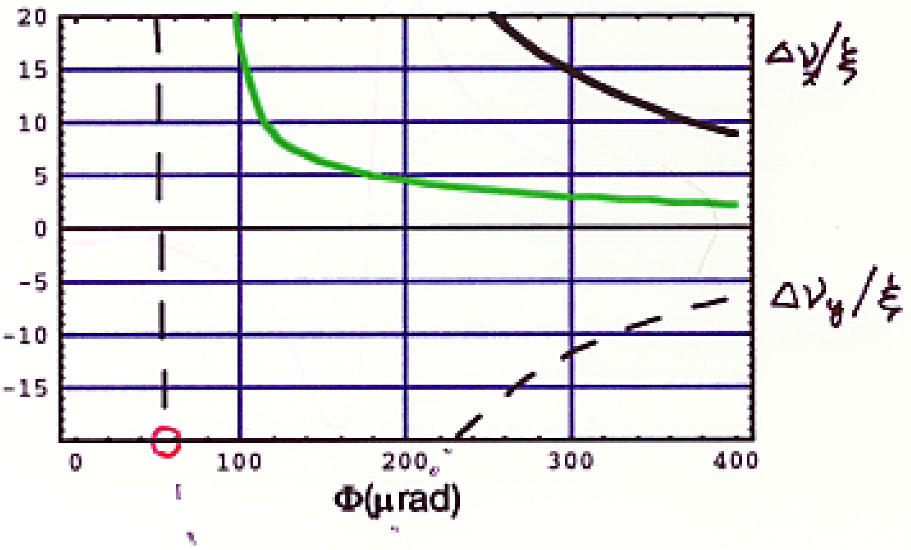
$$\frac{(\Delta\nu_y)_\Phi^{SHC}}{\xi} = \frac{8}{\sigma_s'}\int_0^{l_{int}} \exp\left(-\frac{\gamma\Phi^2 s^2}{2\varepsilon_n\beta^*\left(1+s^2/(\beta^*)^2\right)}\right)ds - \frac{(\Delta\nu_x)_\Phi^{SHC}}{\xi} \tag{2}$$

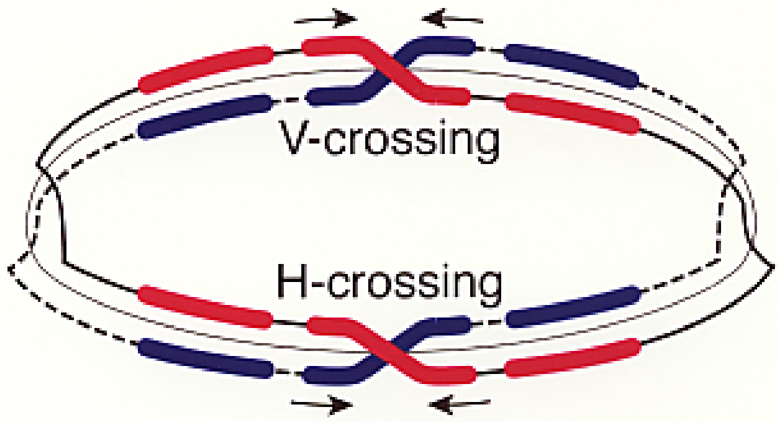
where crossing in the vertical direction is assumed and $2\ell_{int}$ is a size of the interaction region, $2l \langle\langle 2l_{int} \langle\langle \sigma_{sb}$.

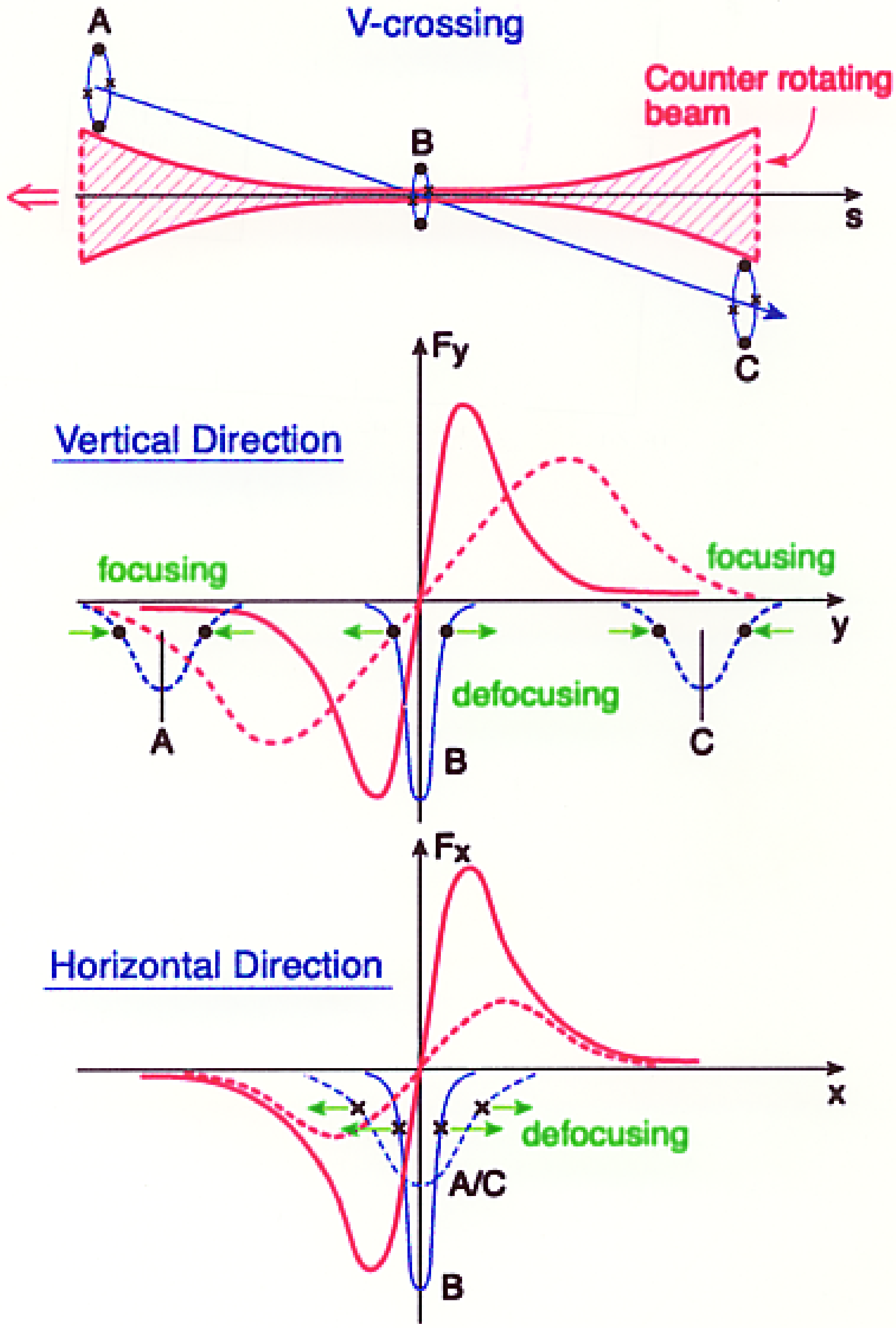
- **In the limit of $\Phi = 0$, $2l_{int} = \sigma_s'/2$, Eqs. (1), (2) become unity.**

The numerical values for both directions are shown as functions of the crossing angle Φ below.

Black: horizontal, dash: vertical, green: sum

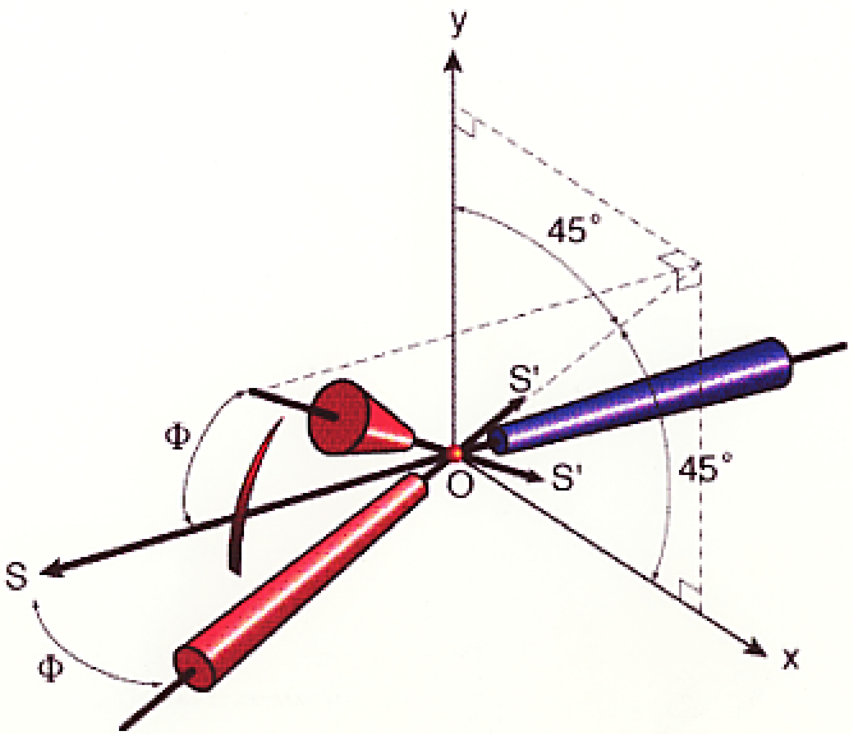



V-crossing
H-crossing

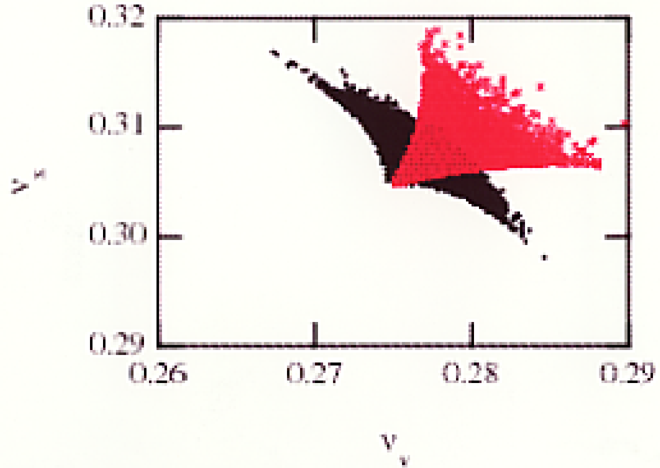


V-crossing
A
B
C
Counter rotating beam
s
Fy
Vertical Direction
focusing
focusing
defocusing
y
A
B
C
Fx
Horizontal Direction
defocusing
x
A/C
B

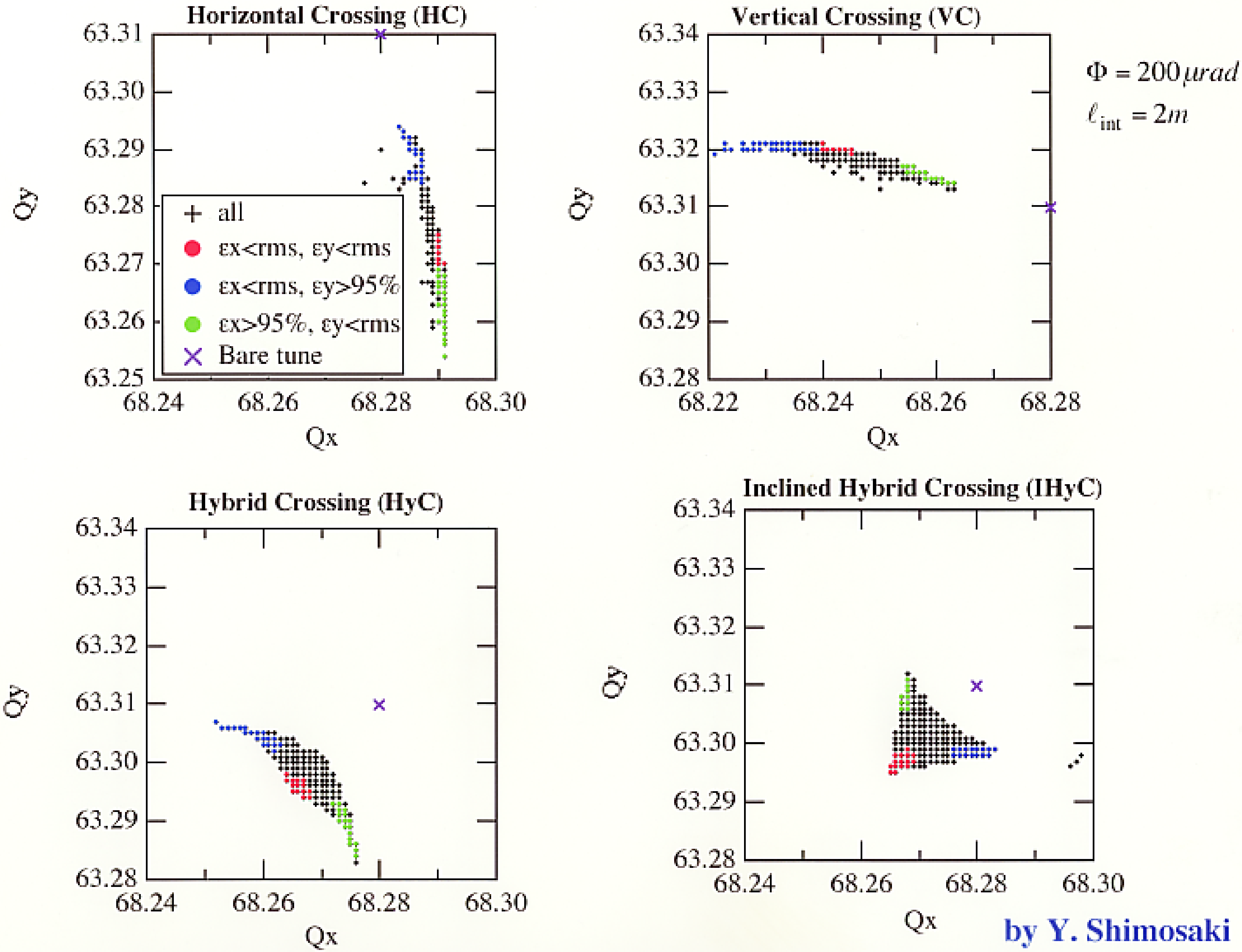
Inclined Crossing & Beam-beam Tune Spread



For a case of LHC

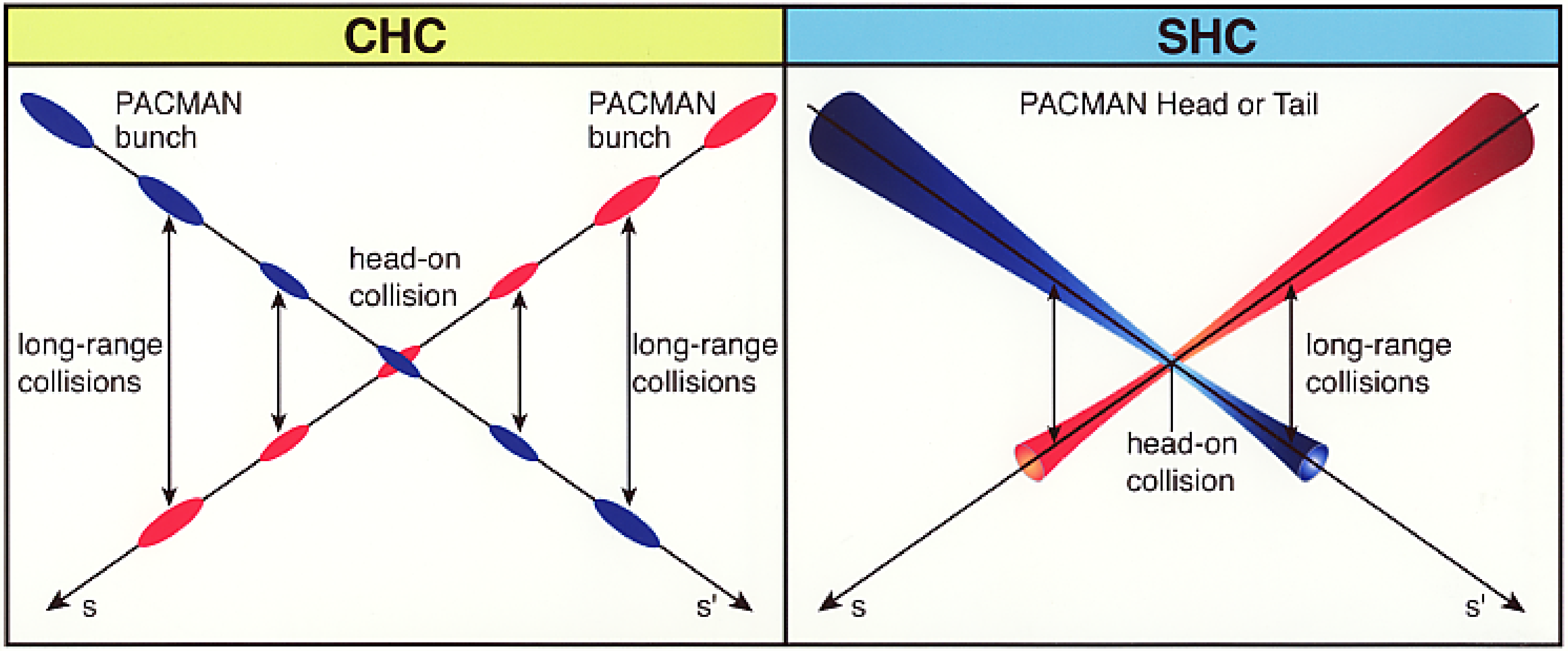


Black: Hybrid crossing
(Vertical cross at North IR and horizontal cross at South IR)
Red: Inclined hybrid crossing



by Y. Shimosaki

PACMAN EFFECTS



Effect Abnormal COD Abnormal Q_x, Q_y Abnormal β_x, β_y	CHC	SHC
	yes	yes
Fraction of PACMAN bunches/particles	15/72 for LHC	mixed in the entire superbunch
Simulation work	done	not yet

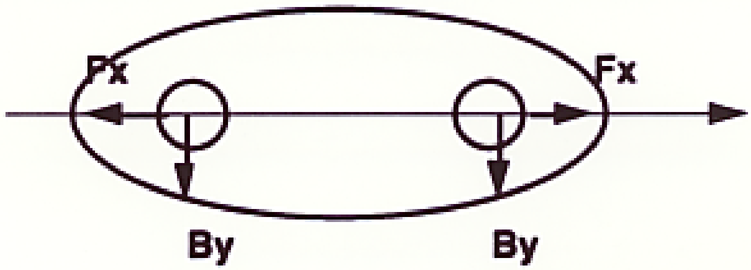
Heat Load

Cooling capacity of a vacuum chamber embedded in the super-conducting magnet is limited. A few W/m. Heat load originated from circulating beams is serious problem.

Item	remarks	CHC	SHC
Synchrotron radiation	$P = 7.36 \times 10^{-21} \frac{N}{R(m)\rho^2(m)}\left(\frac{E}{mc^2}\right)^4$ simply proportional to *N*	200mW/m/ring for LHC	Significant for high luminosity operation
Joule-loss due to wall current	Heat power averaged over τ $\overline{P} = \frac{1}{\tau}\int_0^\tau dt \int_V \frac{\lvert i \rvert^2}{\sigma} dx^3$ τ: revolution time i: wall current σ: electric conductivity	70mW/m for LHC	Relatively small because of small magnitude of high frequency components in wall current
Electron cloud * pointed out and esimated by F.Zimmermann	Electrons accelerated in beam-charge potential or induced electric fields proportional to the fall-off in line density hit vacuum chamber	Serious because many short bunches place in the entire ring	much reduced quite few fall-off in line density

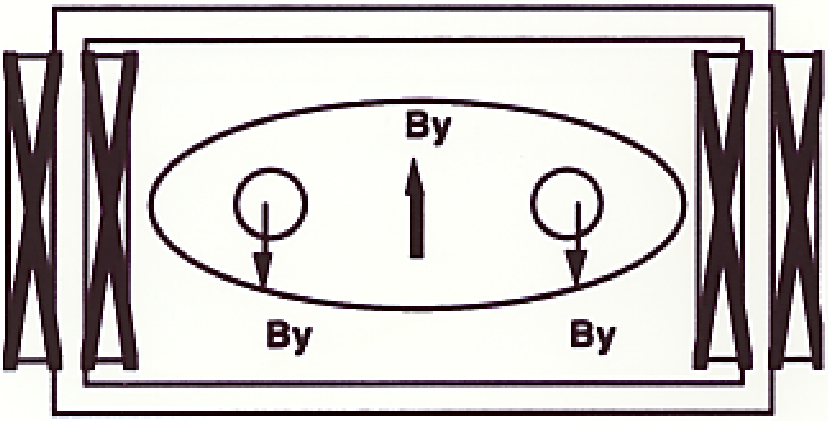
Dipole-kicks Compensator

- Dipole kicks generated as a result of the long (50m) interaction between counter rotating superbunches



$$x_{cod}(s) = \frac{\sqrt{\beta_x(s)}}{2\sin(\mu/2)} \int_s^{s+c} F_x(s')\sqrt{\beta_x(s')}\cos\left[\frac{\mu}{2} - |\Psi(s) - \Psi(s')|\right] ds'$$

- Correction by steering magnets placed along beam line, excitation of which must be scaled with the beam current



- same for vertical crossing in Hybrid Crossing Scheme and Inclined Crossing Scheme

Synchrotron Radiation

■ **Radiation loss/turn of a single particle with mass of *m* and energy *E* traversing along the circle with curvature of ρ**

$$U_0 = \frac{2\alpha hc}{3\rho}\left(\frac{E}{mc^2}\right)^4$$

where α: fine structure constant, $1/137$

h: Planck constant, $6.65\times10^{-34}[J][\text{sec}]$

$(1eV = 1.6\times10^{-19}[J] = 1.6\times10^{-19}[W][\text{sec}])$

$$U_0 = 6.06\times10^{-9}\frac{1}{\rho(m)}\left(\frac{E}{mc^2}\right)^4 \text{ [eV]}$$

■ **Radiation loss/sec by a beam consisting of a total number of protons of *N***

$$NU_0 f_{rev} \quad \text{where } f_{rev} = \frac{c}{2\pi R}$$

■ **Radiation loss/unit length in bending region**

$$P = \frac{NU_0 f_{rev}}{2\pi\rho} \qquad N = N_b \bullet k_b$$

$$= 7.36\times10^{-21}\frac{N_b k_b}{R(m)\rho^2(m)}\left(\frac{E}{mc^2}\right)^4 \text{ [W]/[m]}$$

	LHC	VLHC
N_b	1.05×10^{11}	1.25×10^{10}
k_b	2835	20,000
E (TeV)	7	50
R (m)	4,242.9	14.16
B (T)	8.386	12.5
ρ (m)	2,784.3	13,300
P (W/m/ring)	0.206	5.9

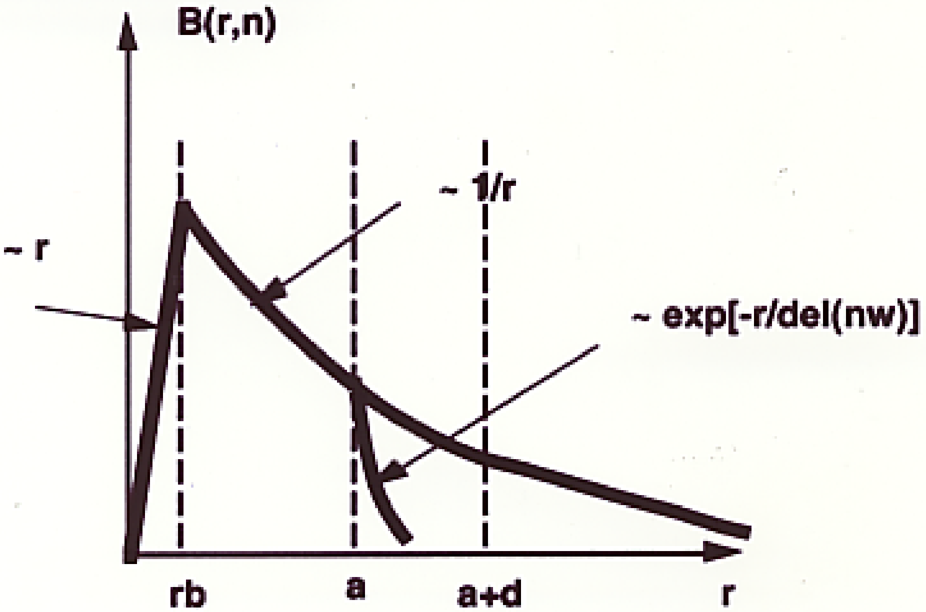
Joule Loss due to Wall-current

■Joule –heat per ring at a certain time

$$P(t) = \int_V \vec{E} \bullet \vec{i}\, d^3x \quad V\text{: vacuum chamber volume}$$

where $\vec{i} = \sigma \vec{E}$

■Boudary condition and magnetic fields generated by beam current and wall-current



■Heat power averaged by revolution time of τ

$$\overline{P} = \frac{1}{\tau\sigma} \int_0^\tau dt \int_V d^3x \left\{ \left| \vec{i} \right|^2 \right\}$$

$$\text{where } \vec{i} = \sum_{n=1}^{\infty} \vec{i}_n,\ \vec{i}_n = \frac{I^n(t)}{2\pi a \delta(n\omega)} \Theta(r - (a + \delta(n\omega))\vec{k}$$

$$I^n(t) = 2\langle I \rangle A_n \cos(n\omega t),\ \langle I \rangle\text{: averaged current}$$

■ Heat power loss per unit length

$$\frac{\overline{P}}{C_0} = 2\langle I \rangle^2 \sum_{n=1}^{\infty} \frac{\rho}{2\pi a \delta(n\omega)} A_n^2$$

Collider Parameters

LHC

	Unit	CHC	SHC
Storage energy	TeV	7	7
Peak luminosity	$cm^{-2}s^{-1}$	10^{34}	1.5×10^{35}
Number of interaction points		2	2
Circumference	km	26.7	26.7
Revolution frequency	kHz	11.2	11.2
Injection energy	GeV	450	450
Transverse normalized emittance, rms (H&V, flat-top)	μmrad	3.75	3.75
Initial bunch intensity		1.1×10^{11}	8.77×10^{13}
Number of bunches		2835	46
Total protons per beam		3.12×10^{14}	4×10^{15}
Average beam current	A	0.56	7.23
Synch. Radiation loss/beam	W/m	0.216	2.8
Bunch spacing	μs(m)	0.025 (7.48)	1.93 (580)
Bunch length rms/full	m	0.075 /*****	*****/150
Beam occupation ratio	%	2	26
Crossing angle	μrad	200	400
β^*	m	0.5	0.5
rms beam size σ^*	m	1.58×10^{-5}	1.58×10^{-5}
Acceleration energy	TeV	6.55	6.55
Acceleration period	sec	1200	1200
Acceleration voltage/turn	kV	480	480
Induction cell rep-rate	kHz		518
Unit induction cell length	m		0.2
Unit induction cell voltage	kV		2.5
Total No. of A-ICs			192
Total length for A-ICs	m		38.4
Core-loss of unit cell	kW		15
Total core-loss during accel.	MW		2.88

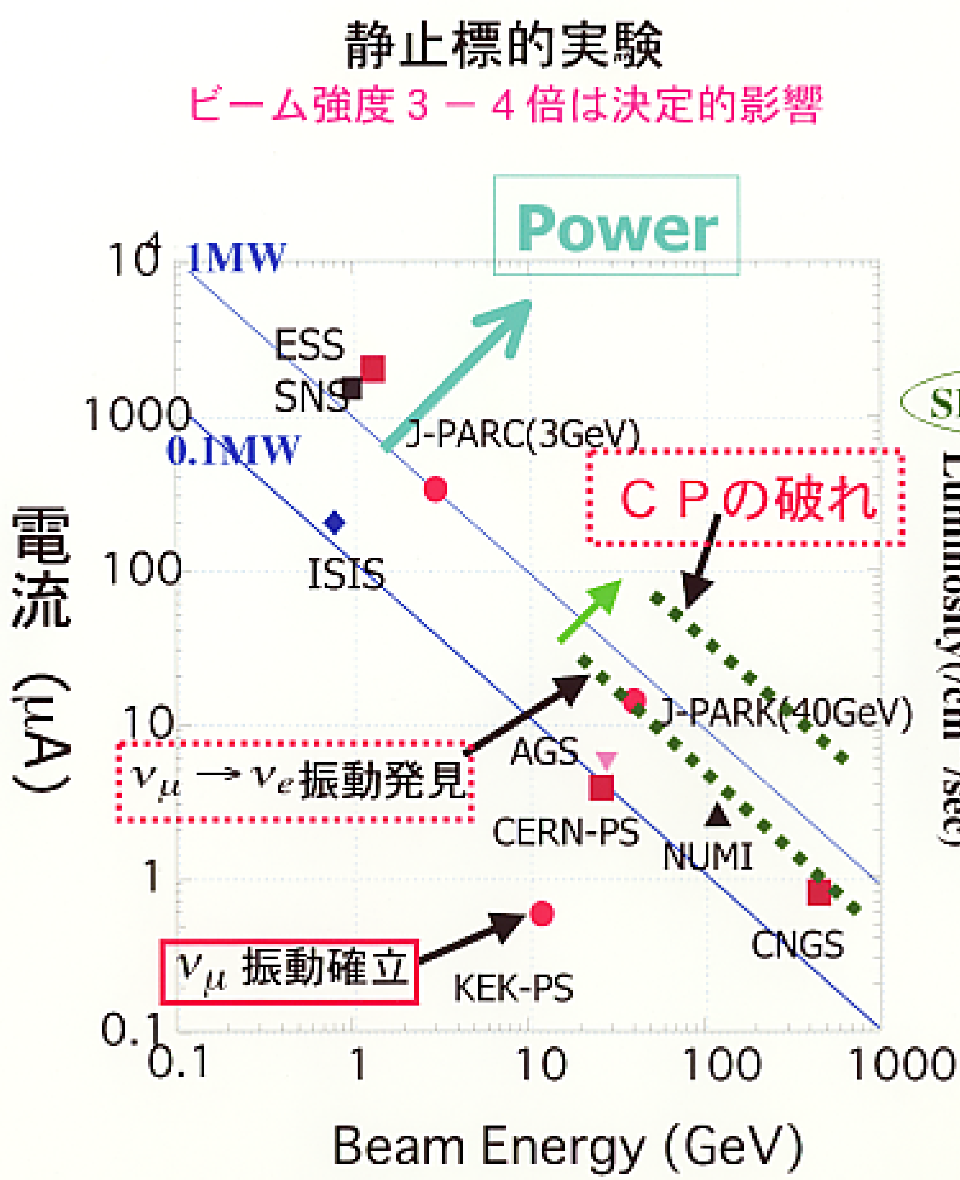
VLHC 1st stage (Baseline design)

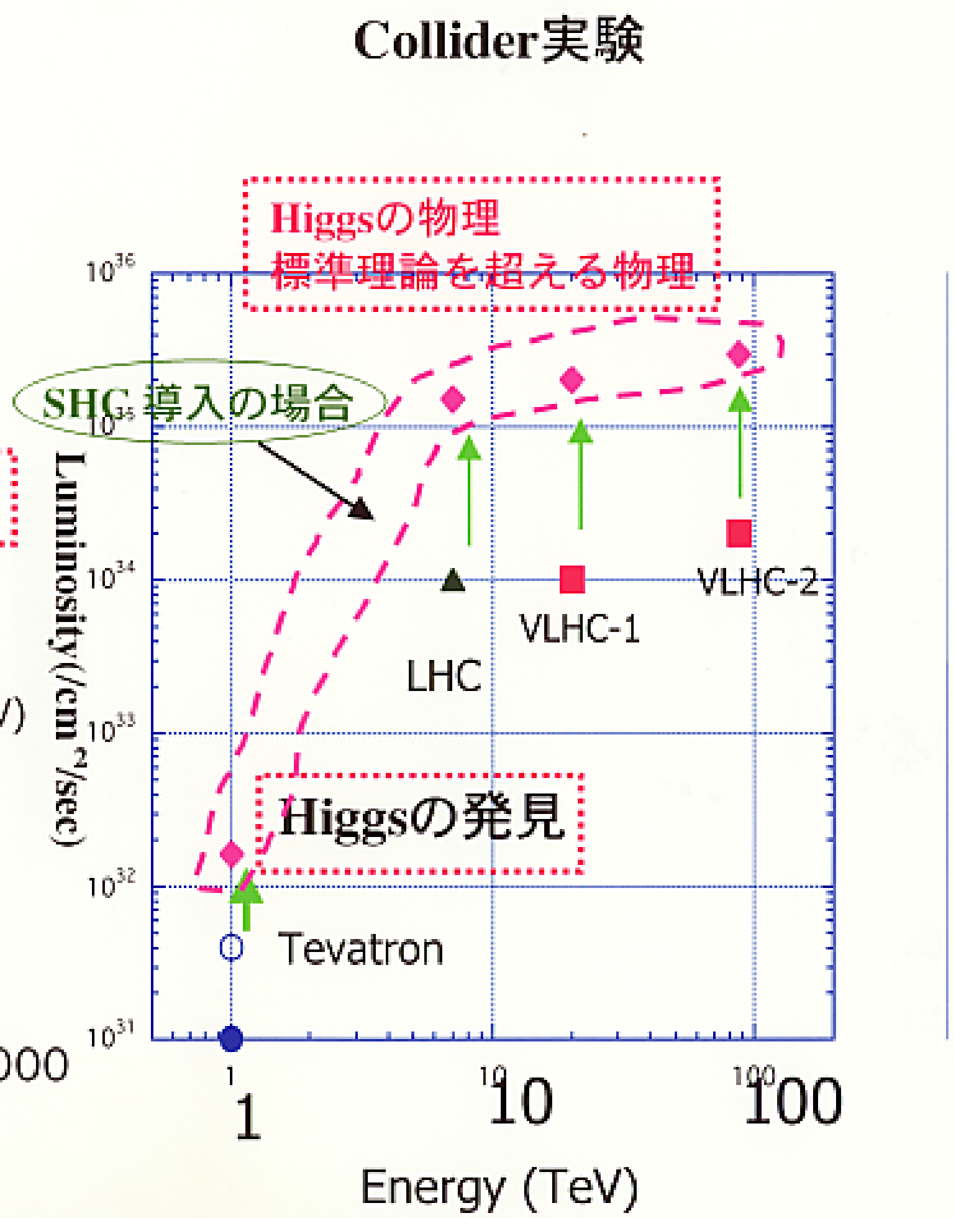
	Unit	CHC	SHC
Storage energy	TeV	20	20
Peak luminosity	$cm^{-2}s^{-1}$	10^{34}	1.5×10^{35}
Number of interaction points		2	2
Circumference	km	233.037	233.037
Revolution frequency	kHz	1.286	1.286
Injection energy	TeV	0.9	0.9
Transverse normalized emittance, rms (H&V, flat-top)	μmrad	1.5	1.5
Initial bunch intensity		2.6×10^{10}	5.2×10^{13}
Number of bunches		37152	335
Total protons per beam		9.66×10^{14}	1.74×10^{16}
Average beam current	A	0.195	3.5
Synch. radiation loss/beam	W/m	0.03	0.538
Bunch spacing	μs(m)	0.019 (5.65)	2.32(695)
Bunch length rms/full	m	0.03 /*****	*****/150
Bunch occupation ratio	%	1.2	21.6
Crossing angle	μrad	153	400
β^*	m	0.3	0.3
rms beam size σ^*	m	0.46×10^{-5}	0.46×10^{-5}
Acceleration energy	TeV	19.1	19.1
Acceleration period	sec	1000	2000
Acceleration voltage/turn	MV	14.85	7.425
Energy compensation/turn	keV	38	
Induction cell rep-rate	kHz		431
Unit induction cell length	m		0.2
Unit induction cell voltage	kV		2.5
Total No. of A-ICs			2970
Total length for A-ICs	m		594
Core-loss of unit cell	kW		12.5
Total core-loss during accel.	MW		37

内外の協力体制

機関名	種類	研究内容
東京工業大学・創造エネルギー専攻　堀岡研究室、堀田研究室	共同開発研究	磁性体の特性試験、特性データーベース作り、小規模装置での 1MHz 動作試験、ビームローディング試験、SI サイリスタの特性試験、新型素子の検証試験
電源製造メーカー	装置開発	電源モジュレーターの開発支援
日本ガイシ	半導体素子開発（特許権）	低温動作 SI サイリスタの開発、耐放射線テスト
日立金属	磁性体開発（特許）	低損失ファインメットの開発支援
FNAL フェルミ国立加速器研究所	共同研究	Super-bunch 加速シナリオの研究、反陽子 Recycler Ring での RF バリアーバケット・ビームハンドリングの共同実験
CERN ヨーロッパ原子核研究所	共同研究	ビーム・ビーム相互作用を含めスーパーバンチビーム物理の研究
BNL ブルックヘブン国立研究所	共同研究	Laser-asist H^- の対称ペインテイング入射法の試験研究
LBNL/LLNL ローレンスバークレー・リバモア国立研究所	情報交換、共同著作	磁性体、Switching 素子特性データーベースの共有、Springer よりテキスト「誘導加速器」の共同執筆

7　陽子加速器と素粒子物理の展開





8　まとめ

■誘導加速シンクロトロンは最近の磁性体とパワー半導体スイッチング素子の新展開をベースに提案された我々独自のアイデアである。

■基礎科学、応用科学にこの50 年来貢献して来たRFシンクロトロンに取って代わり得る。

■実現に必要な要素技術の大部分が日本発の物であり、国内メーカーのバックアップが期待出来る。安定／高速スイッチと低損失コア材の実現

■更に公立の機関研究のバックアップにより、先進的素子の利用が可能となれば、基盤技術から応用までの全分野をカバー出来る筈。

■実証後、既存加速器に導入されれば、長大なスーパーバンチと呼ばれるビームの供給でその能力を格段に向上させ得る。
先ず、ニュートリノ振動解明（ν_μの精密測定、 ν_μ->ν_eの発見）
へのドラスチックな貢献

■誘導加速シンクロトロンの概念の必然的延長であるスーパーバンチコライダーはこれまでの衝突型加速器の常識をうち破るであろう。
標準理論最後の未発見粒子　Higgs 粒子　の発見
標準模型を超える　超対称性粒子　の発見