Ion Accelerators

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1.	Classification of Accelerators
2.	Brief History
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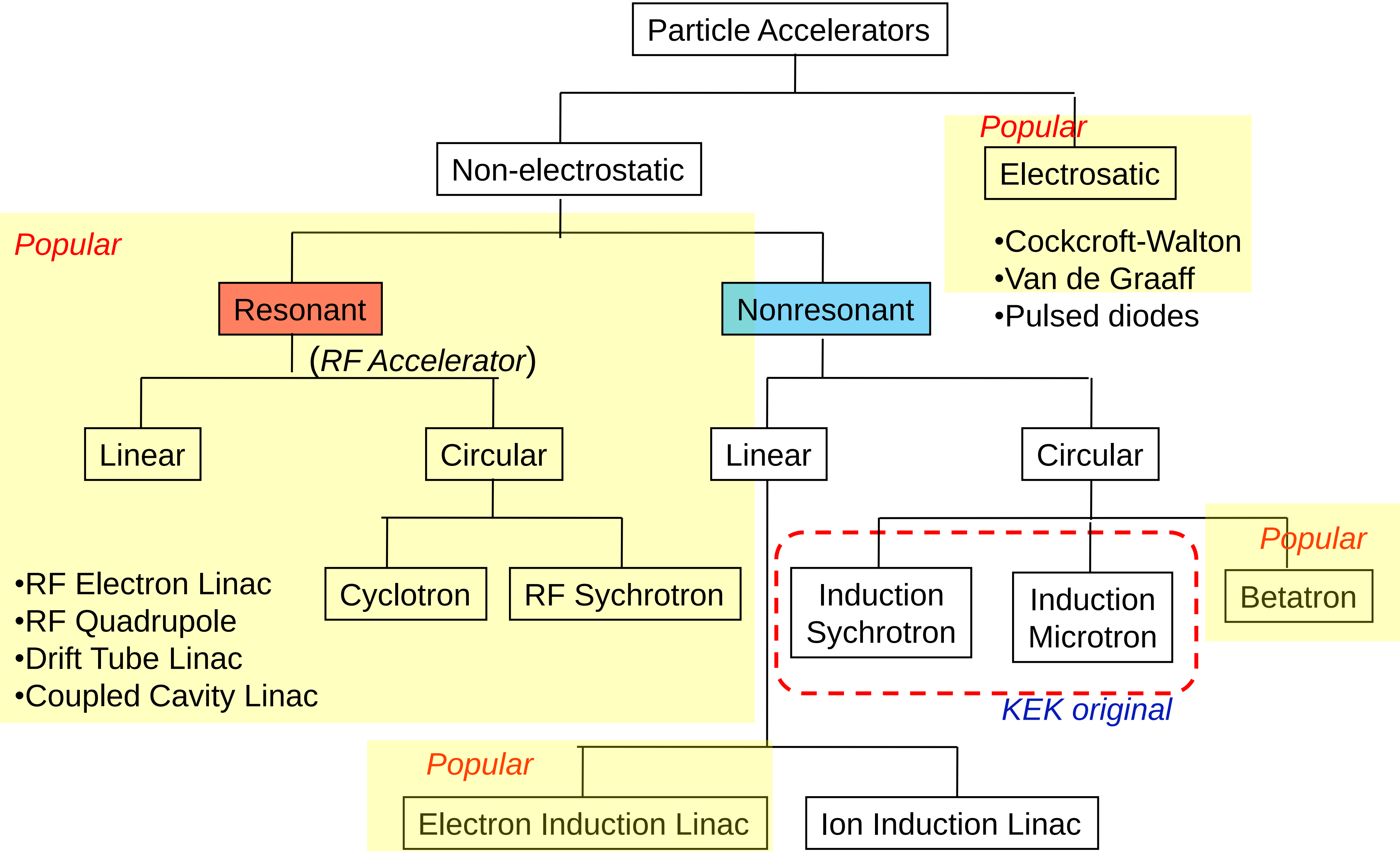
	Accelerator Complex for Exotic Particles
	Gigantic Accelerator Complex for Heavy Ion Inertial Fusion
	Low, Medium Energy Ion Accelerators
4.	Novel Accelerator for Ions

Classification of Accelerators

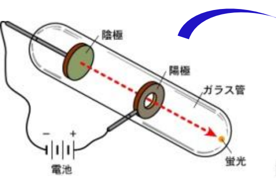


from Induction Accelerators (Springer 2010), K. Takayama and R. Briggs

Historical Evolution of Circular Hadron Accelerators

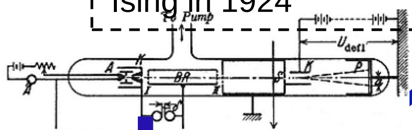
Evolution of RF accelerator

(RF technology)



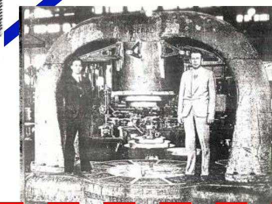
Cathode tube

Two Gaps Accelerator
Ising in 1924



Wideröe in 1928

Cyclotron
Lawrence in 1931



Synchrotron (Weak-Focusing)
McMillan, Veksler in 1945

Electron Cyclotron
Veksler in 1945

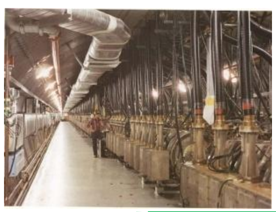
3 GeV Cosmotron at BNL
6 GeV Bevatron at Berkeley

Evolution of Induction accelerator

Betatron
Wideröe in 1928

Betatron
Kerst in 1941

Microtron
Schwinger, Schiff in 1946
Ito and Kobayashi in 1947



Linear Betatron
Christofilos, Veksler in 1956

Synchrotron (Strong-Focusing)
Christofilos in 1950
Courant, Snyder, Livingston in 1952

Non-resonant

(Solid-state power device)

Induction Synchrotron
at KEK in 2000

Induction Microtron
at KEK/TIT in 2012

28 GeV AGS at BNL

Tevatron, RHIC, LHC, (KEKB) — Collider

FNAL Main Injector, J-PARC, SNS — High Intensity Driver

(Synchrotron Radiation Source)

Hadron driver for cancer therapy

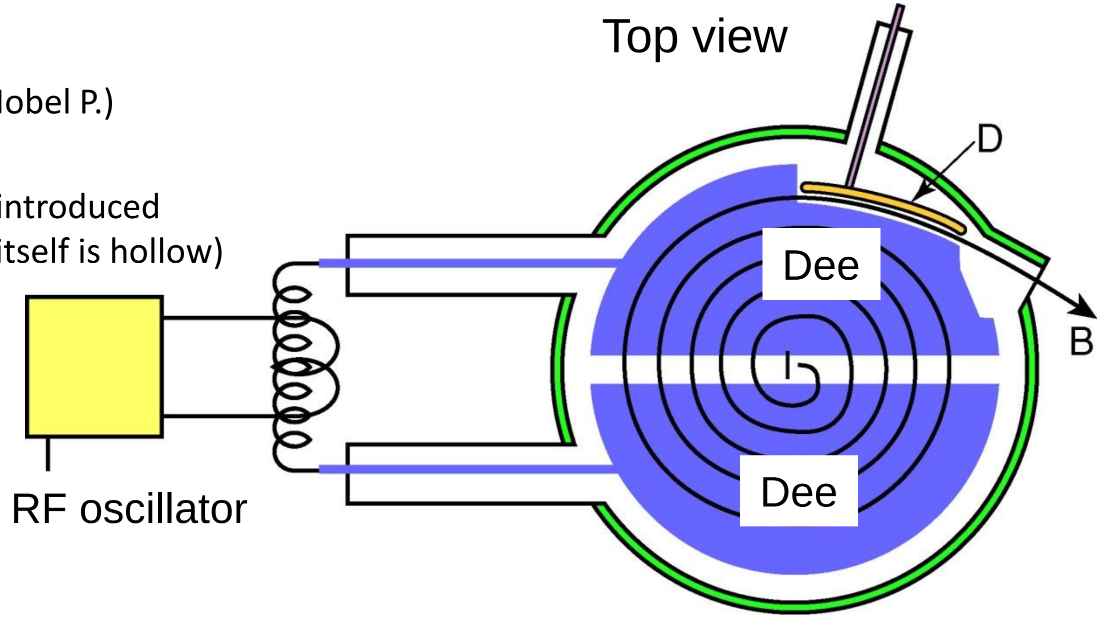
Synchrotron (Separate-function)
Kitagaki in 1953

(Modern technology: superconducting, computer, novel mag.materials etc.)

Operation principle of a Classic Cyclotron

1931 E.O.Lawrence , the first cyclotron   (1939 Nobel P.)

Idea: AC voltage or RF (angular frequency ω) is introduced between the gap of Dee electrodes (Dee itself is hollow) as an accelerating midium.



Revolution period

Condition of repeated acceleration :

$$\frac{1}{2}\left(\frac{2\pi r}{v}\right)=\frac{1}{2}\left(\frac{2\pi}{\omega}\right)$$

Period of RF

r: rotation radius, v: velocity

Force balance in the radial direction :

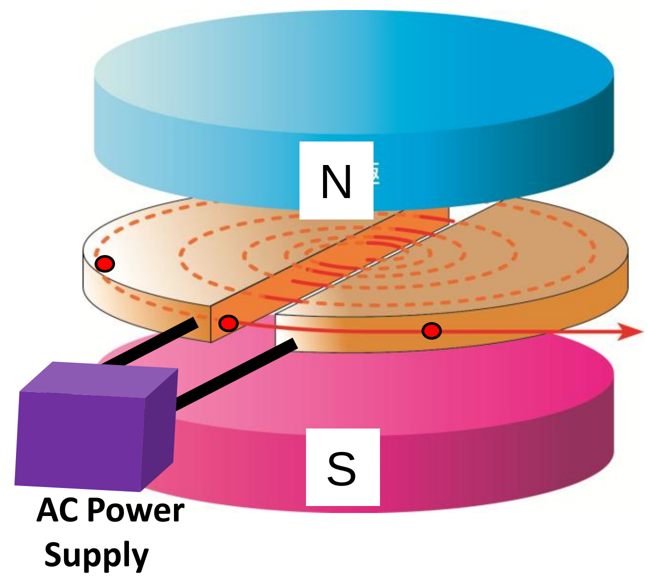
$$m\gamma\frac{v^2}{r}=evB_z \rightarrow \frac{r}{v}=\frac{m\gamma}{eB_z}$$

thus, $\omega=\dfrac{eB_z}{m\gamma}$ r: Larmor Radius

in the non - relativistic limit

$\omega = const.$ Note: ω does not depend the orbit radius r.

D: High voltage deflector
I: Ion source
B: Exit
Spiral : track of ion



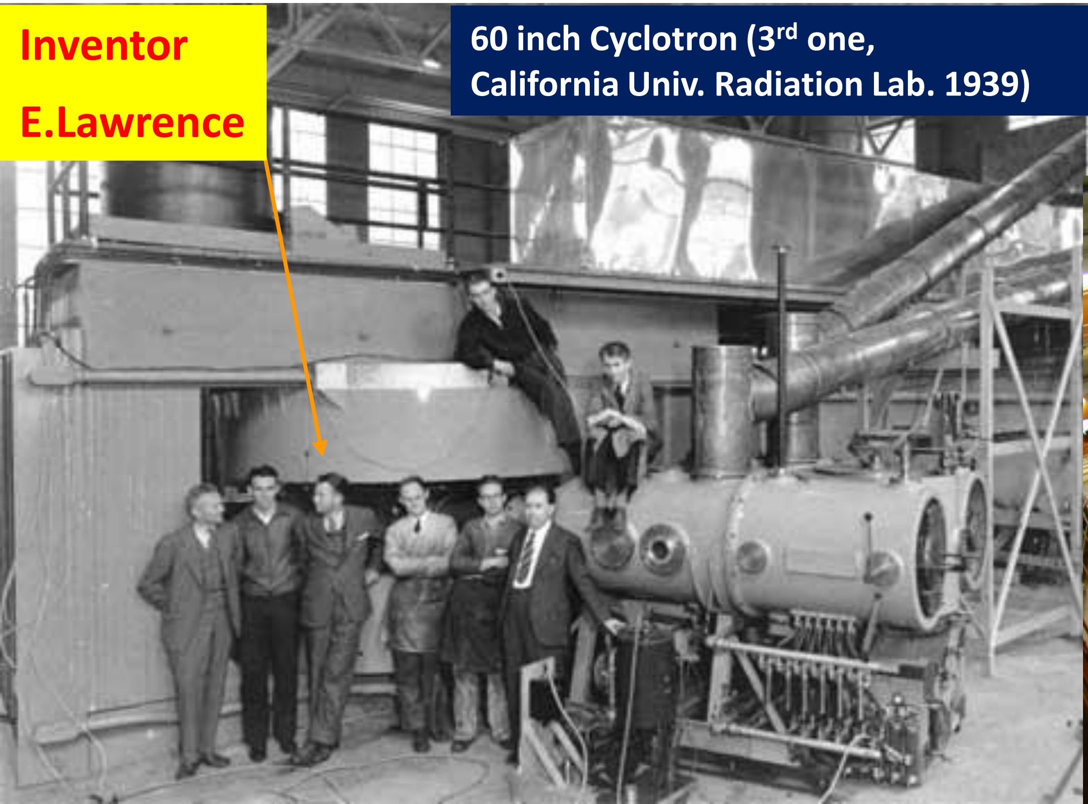
• Once ω and B are fixed,
any ions with the same (e/m) can be accelerated in the cyclotron.

Actually constructed cyclotrons

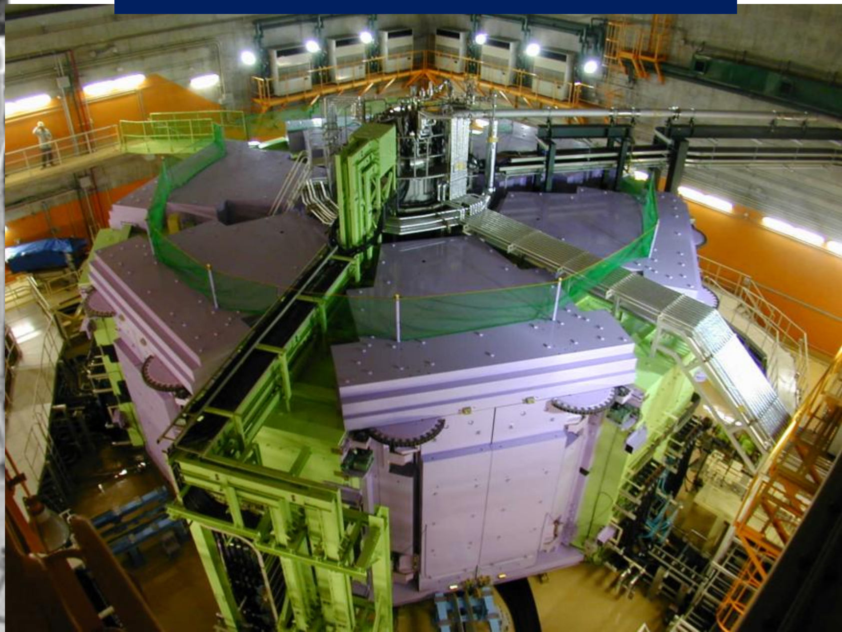
1st Cyclotron

4.5 inch table top cyclotron
(1931)
H- ion
Acieved energy : 80 keV,
Accelerating voltage : 1.8 kV

60 inch Cyclotron (3rd one, California Univ. Radiation Lab. 1939)

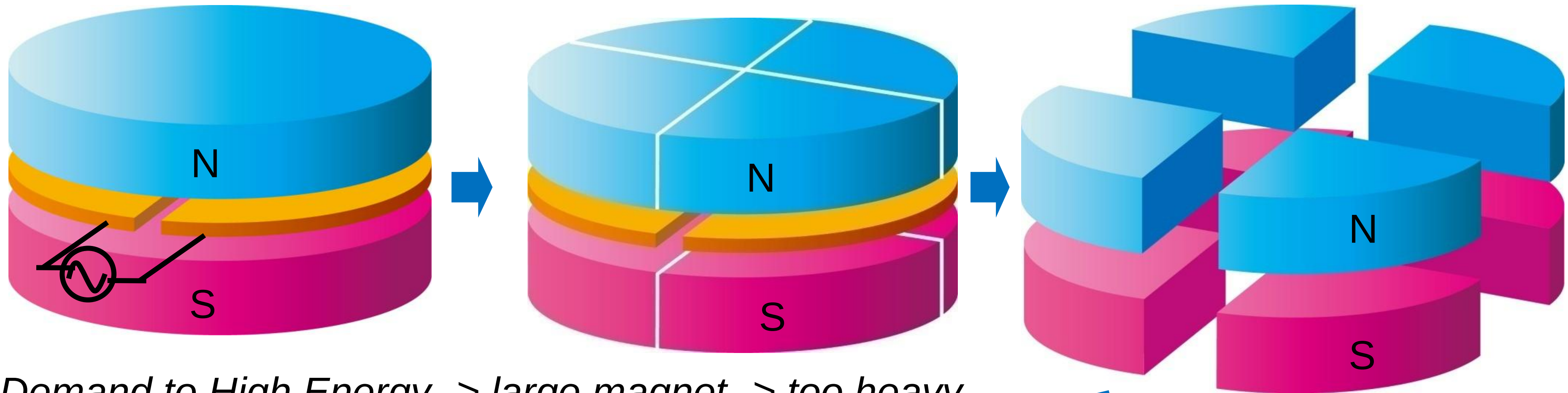


The latest Cyclotron
Super-conducting Ring Cyclotron
（RIKEN, 2006）



Evolution of Circular Accelerators

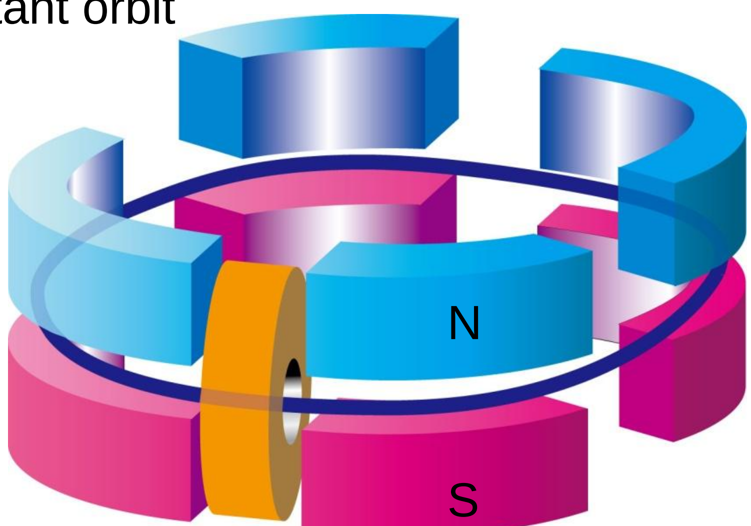
p (mometum) $\propto B\rho$ (magnetic regity) *Possible solution −> Splitting of Magnet Pole*



Demand to High Energy -> large magnet -> too heavy

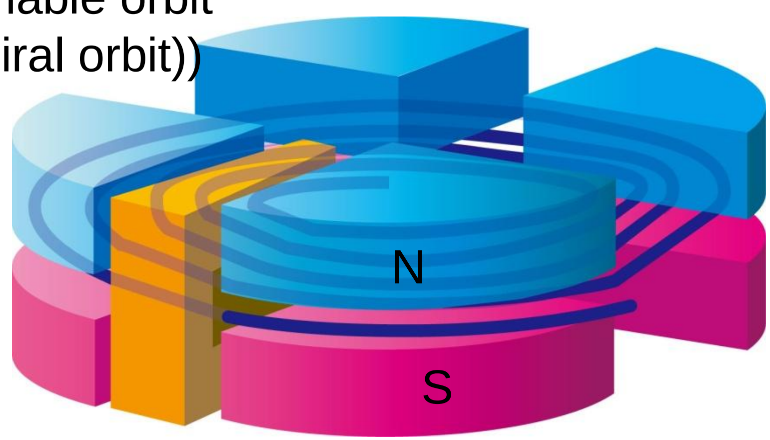
Synchrotron

Variable ***B***
Constant orbit



Sector Type Cyclotron

Constant ***B***
Variable orbit
(spiral orbit))



Synchrotron Basic

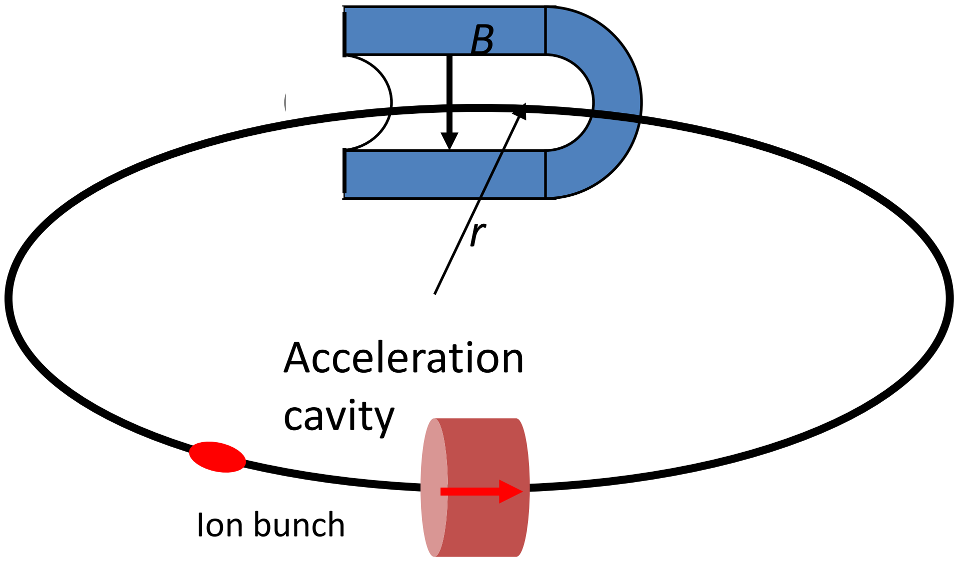
Acceleration in Cyclotron

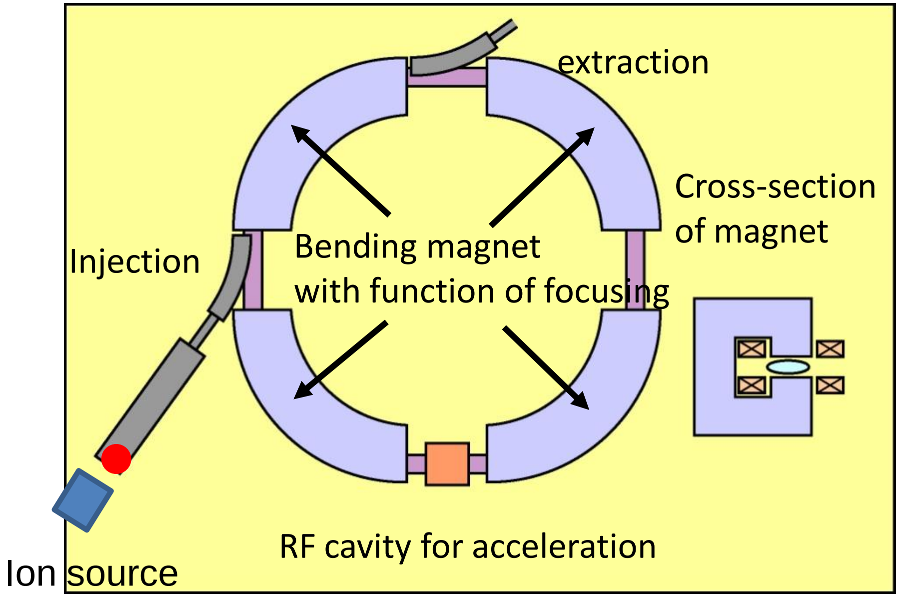
Focusing in Betatron

→ **Synchrotron**

Basic configuration
（top view）

Split bending magnet in which pole face has gradient for focusing both directions



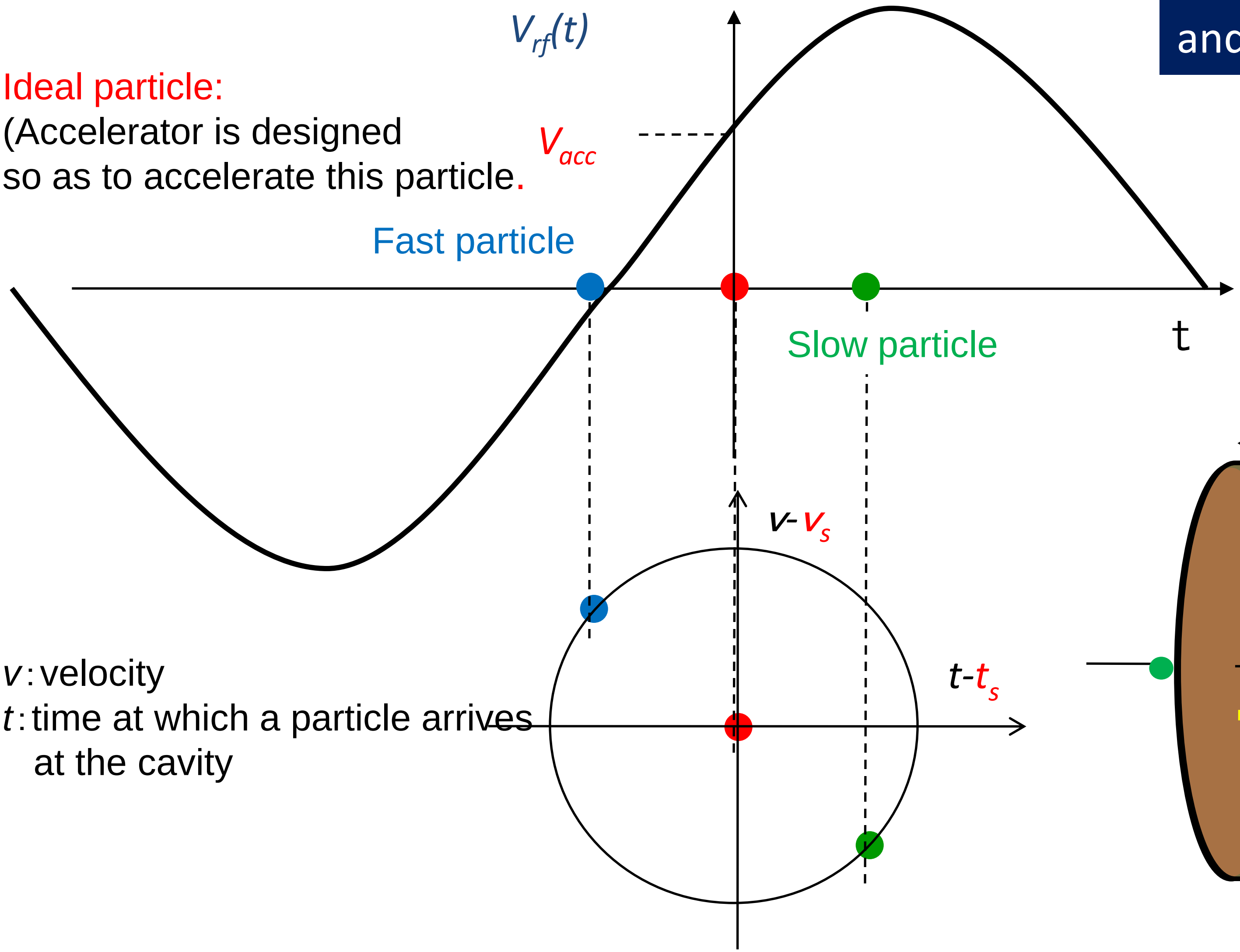


Acceleration voltage/turn:

$V_{acc}=\rho C dB/dt$

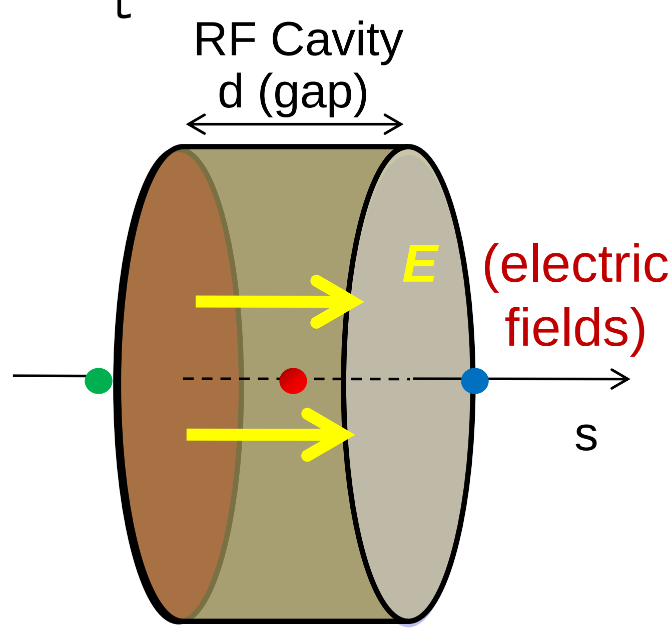
Acceleration and Confinement in the longitudinal direction

RF fields and Particles in acceleration phase



Schematic RF cavity and Electric fields

$$E_z = \frac{V_{rf}(t)}{d}$$



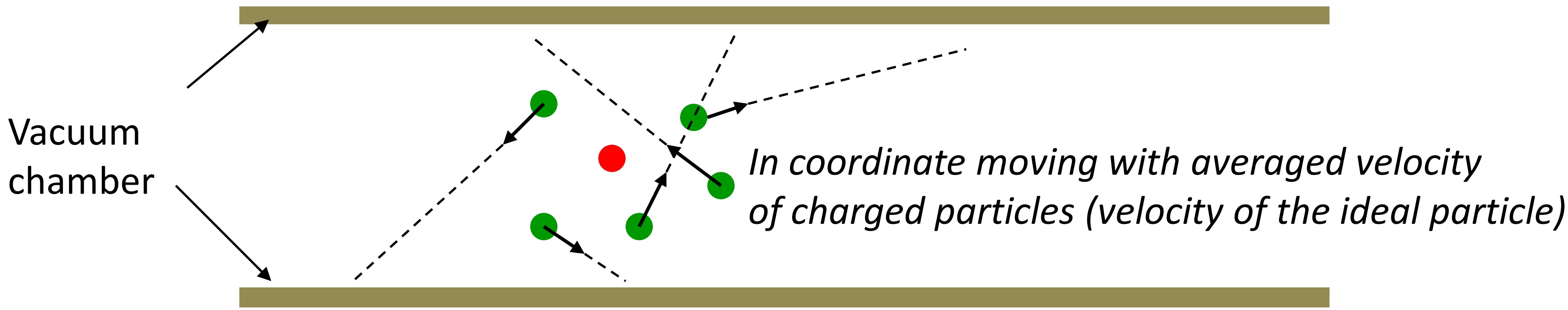
Phase Stability

Acceleration device (RF cavity) is operated so as to accelerate a single particle called an ideal particle. Other particles of 10^{12} ~ 10^{13} can be simultaneously accelerated.

Confinement of Charged Particles with Various Velocity Vector

Particles have various velocity vectors.

Reasons: Intrinsic initial distribution, scattering by residual atoms and molecules, intra-beam scattering (self interaction in the same bunch), effects from amplitude dependent error fields

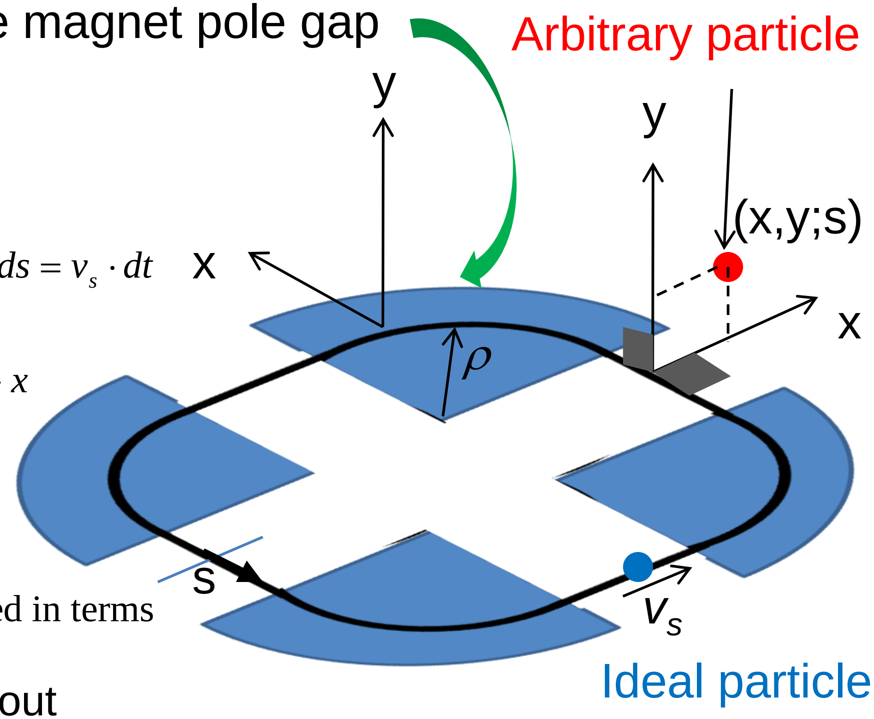


Particles of 10^{10}-10^{12} have to be confined and simultaneously accelerated in a real circular accelerator.

Any confinement forces are required.

$$\frac{d}{dt}\left(m\gamma \cdot v_x\right) = e \cdot v_s \cdot B_y \quad \Rightarrow \quad F$$

Orbit Coordinate and Betatron Motion



Lorentz Equation :

$$m\frac{d(\gamma v)}{dt}=e(E+v\times B).$$

From time coordinate to orbit coordinate (orbit of an ideal particle) $ds = v_s \cdot dt$

Inorder to discuss a small amplitude motion

around this orbit of the ideal particle, introduce x: $r = \rho + x$

Lorrentz force and centrifugal force for the ideal particle ballance,

$$m\gamma\cdot\frac{v_s^2}{\rho} = e\cdot v_s\cdot B_y(0,0)$$

Magnetic fields around the orbit of the ideal particle can be expanded in terms of small x and y,

$$B_x(r,y) = \frac{\partial B_x(0,0)}{\partial y}\cdot y = \frac{\partial B_y(0,0)}{\partial x}\cdot y$$

$$B_y(r,z) = B_y(0,0) - \frac{\partial B_y(0,0)}{\partial x}\cdot x$$

Cancel out

Orbit Equation
(called Betatron Equation)

Orbit equation for an arbitrary particle can be written by,

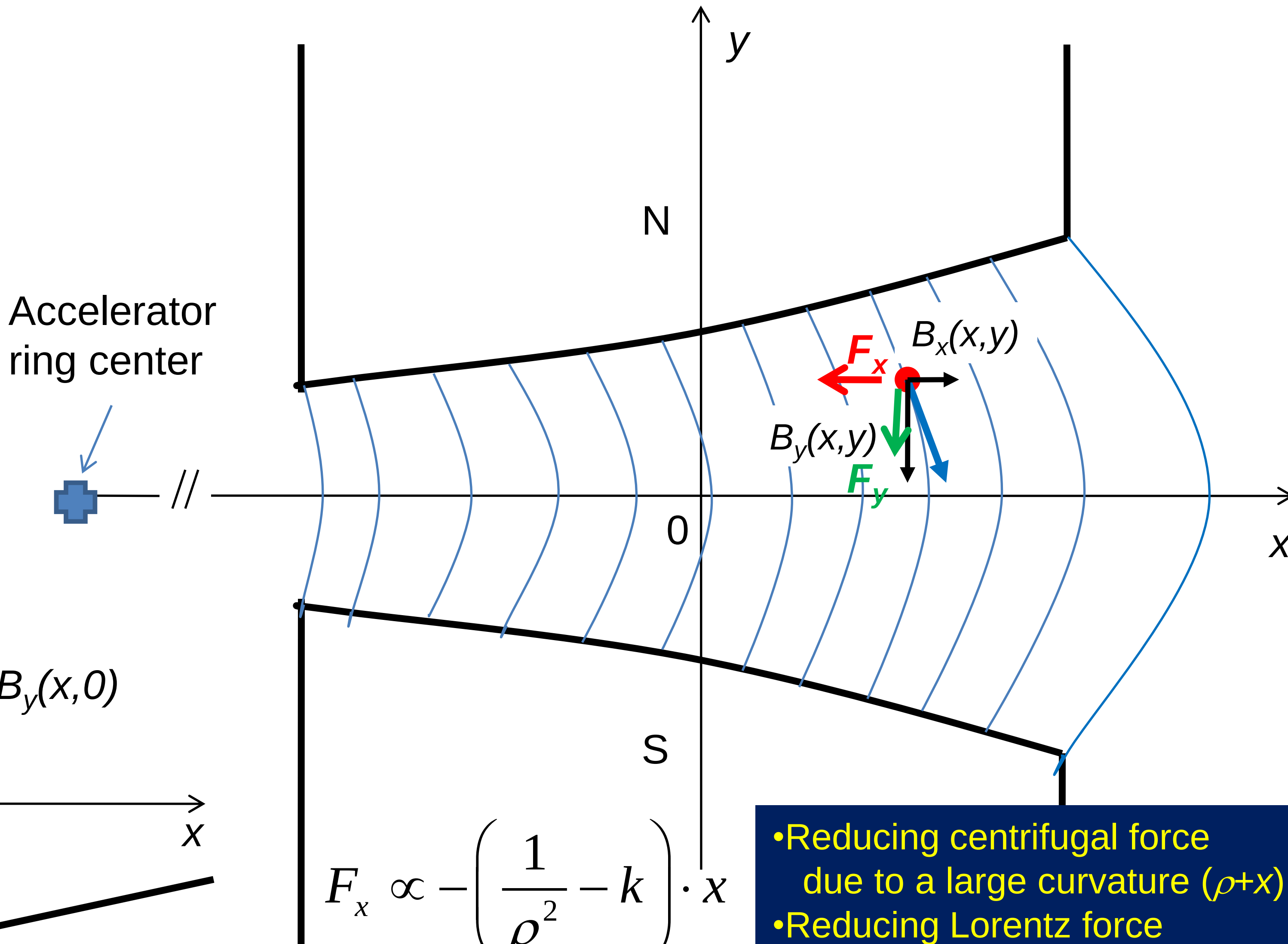
$$m\gamma\cdot\frac{d^2x}{dt^2} - \frac{m\gamma\cdot v_s^2}{\rho + x} = e\cdot(v_s B_y - v_y B_x) \rightarrow \frac{d^2x}{dt^2} - \frac{v_s^2}{\rho} + \frac{v_s^2}{\rho^2}\cdot x = \frac{ev_s}{m\gamma}\cdot\left[B_y(0,0) + \frac{\partial B_y}{\partial x}\right]\cdot x \rightarrow \frac{d^2x}{ds^2} + \left[\frac{1}{\rho^2} - \frac{e}{m\gamma v_s}\left(\frac{\partial B_y}{\partial x}\right)\right]\cdot x = 0$$

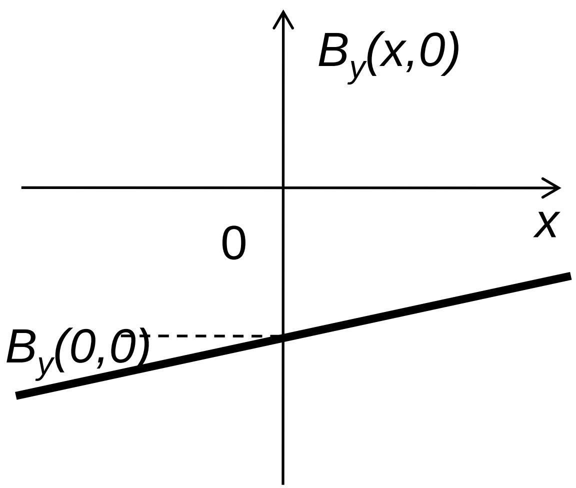
$v_s B_y >> v_y B_x$

$$m\gamma\cdot\frac{d^2y}{dt^2} = -ev_s B_x(x,y) = -ev_s\cdot\frac{\partial B_y}{\partial x}\cdot y \rightarrow \frac{d^2y}{dt^2} + \frac{ev_s}{m\gamma}\left(\frac{\partial B_y}{\partial x}\right)\cdot y = 0 \rightarrow \frac{d^2y}{ds^2} + \frac{e}{m\gamma v_s}\left(\frac{\partial B_y}{\partial x}\right)\cdot y = 0$$

This existence of **field gradients** can give the orbit stability in Betatrons and Synchrorons.

Summary of Forces on a particle in the guiding magnetic fields





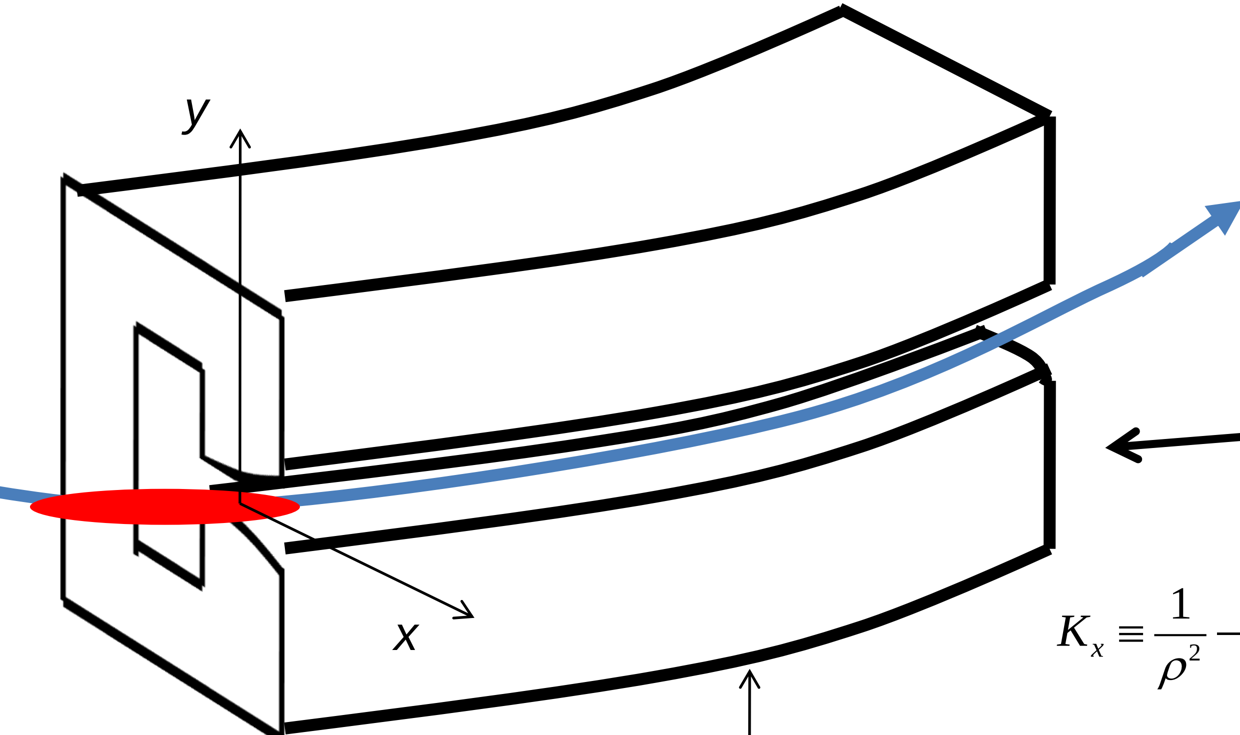
$$F_x \propto -\left(\frac{1}{\rho^2} - k\right)\cdot x$$

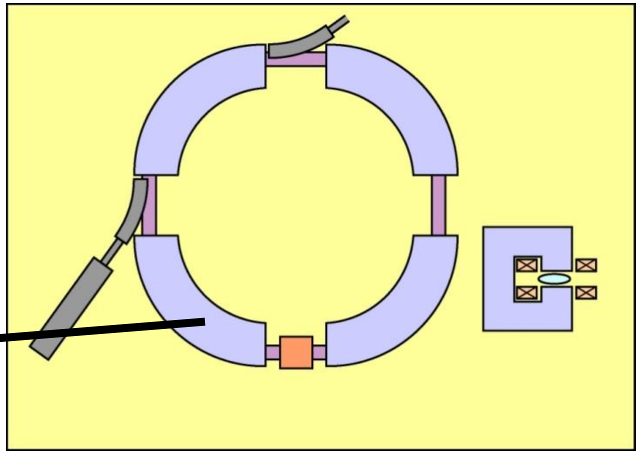
$$F_y \propto -k \cdot y$$

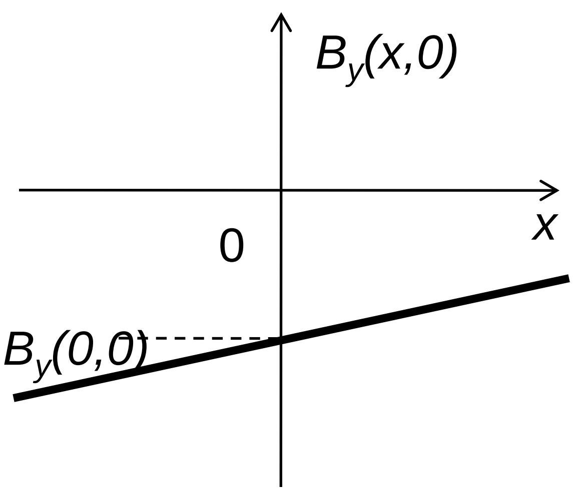
- Reducing centrifugal force due to a large curvature ($\rho+x$)
- Reducing Lorentz force due to $|B_y(x,0)| < |B_y(0.0)|$

- *Additional* B_x

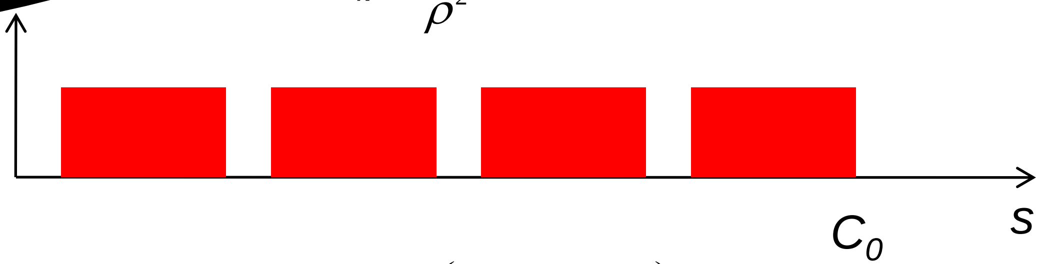
Guiding Magnet and Lattice for a Weak Focusing Synchrotron



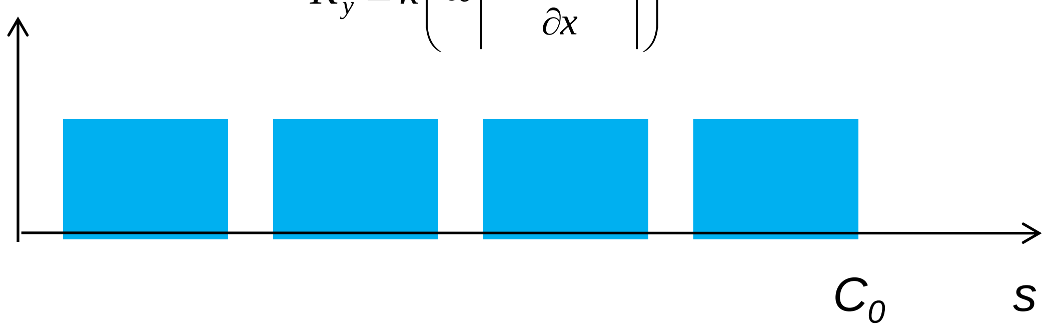




$$K_x \equiv \frac{1}{\rho^2} - k$$



$$K_y \equiv k \left(\propto \left| \frac{\partial B_y(0,0)}{\partial x} \right| \right)$$



1st Synchrotron

Inventor: Prof. E.M.McMillan
awarded Nobel Prize (Chemistry) in 1951
not for invention of Synchrotron
but for discovery of Neptunium using Cyclotron

E=340MeV（electron）
Weak focusing synchrotron constructed in1946

University of California in Berkeley, Radiation Lab. (later LBL)

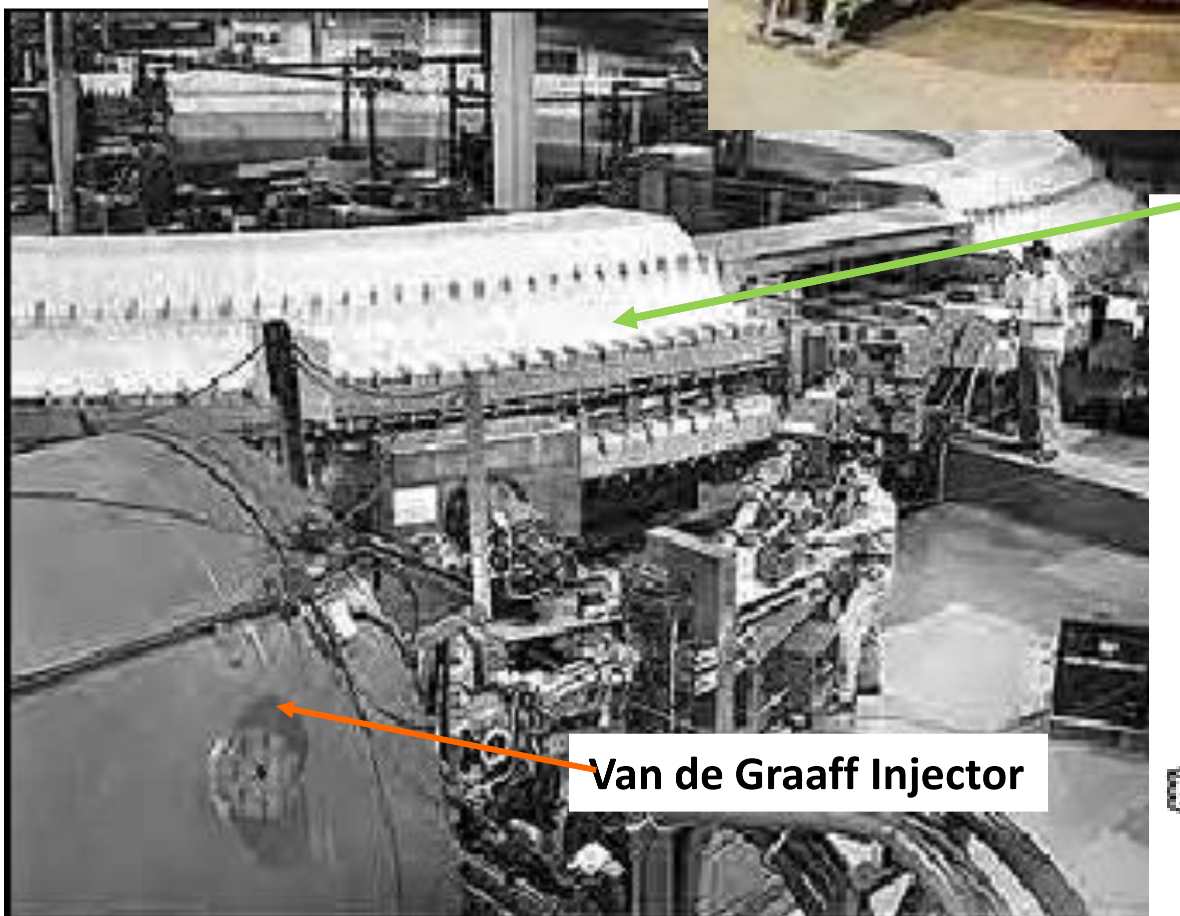
2nd Largest Weak Focusing Synchrotron

Cosmotron (BNL)

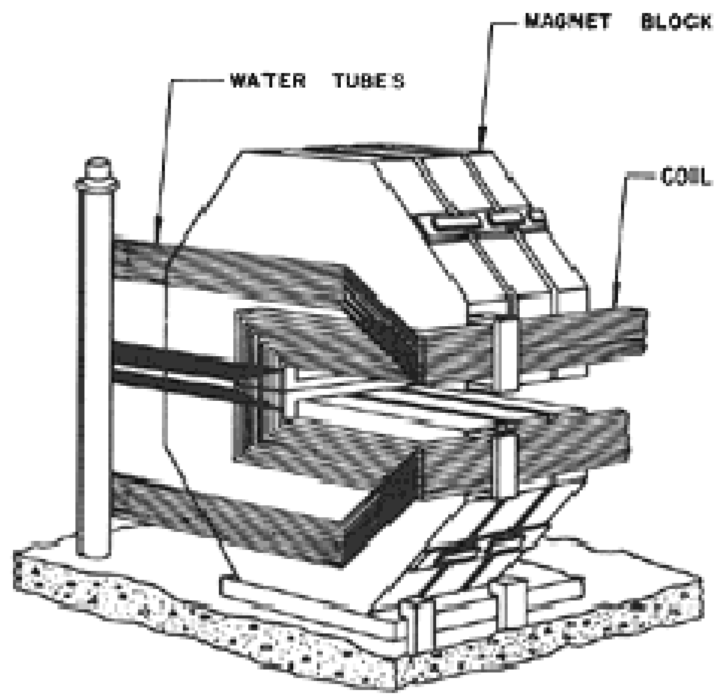
1953-1966

Energy:3GeV

Discovery of K-meson, Vector meson

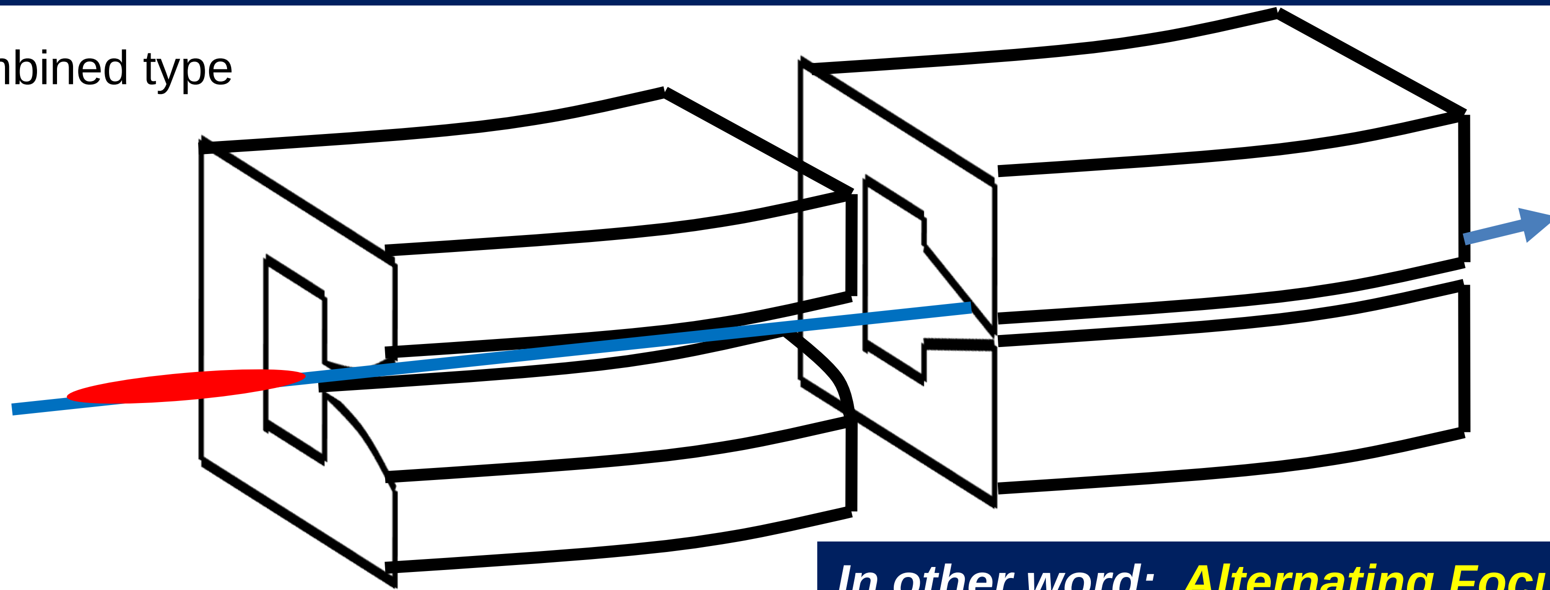


Weak focusing magnet



From Weak Focusing Synchrotron to Strong Focusing Synchrotron

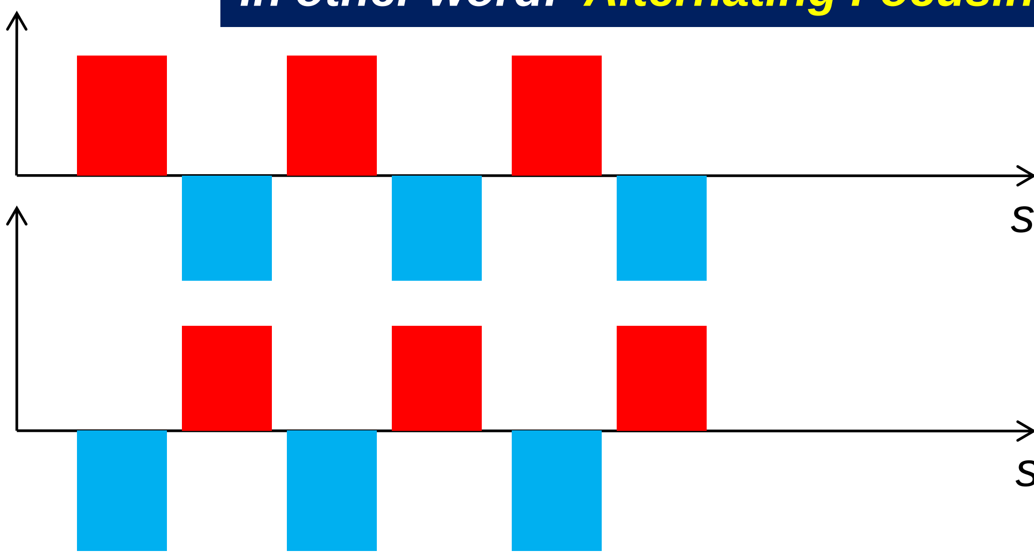
Combined type



In other word: Alternating Focusing

$$K_x \equiv \frac{1}{\rho^2} - k \cong -k \qquad \left(\frac{1}{\rho^2} \ll |k| \right)$$

$$K_y \equiv k$$



It was mathematically proved that the ***combination of focusing and defocusing magnet*** *gives the stability of betatron motion, with a big figure of merit* <u>*in 1950 and 1952*</u>*, which is analogous to* ***guiding of light using focusing lens and defocusing lens****.*

Inventors of Strong Focusing Principle

Nickolas Christofilos
Greek electronics engineer
BNL -> LLNL
Pioneer of linear induction accelerator

Hartland S. Snyder
Co-author of famous paper on
Black-Hall with Oppenheimer

Mourice Goldhaver

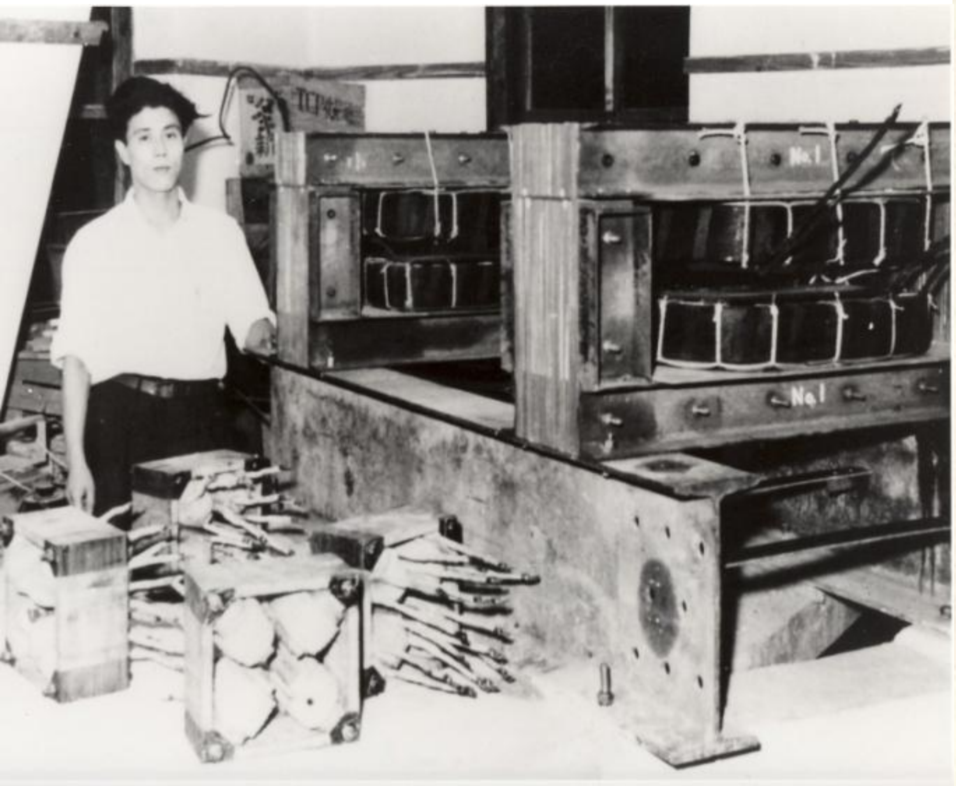
Ernest Courant
Son of famous Mathematician Courant

Stanley Livingston
Pioneer of Cyclotron development with Lawrence

Inventor of Separate-function Type Synchrotron:
Prof. Toshio Kitagaki
(Tohoku University in Japan)

1 month later from publication of Counrant's paper, Kitagaki proved that the same stability can be warranted even if the quadrupole field components in the combined -type bending magnet are separated.

Concept was crucial to realize
Collider
Synchrotron radiation source.



A Focusing Method for Large Accelerators

T. KITAGAKI
Department of Physics, Faculty of Science, Tohoku University, Sendai, Japan
(Received December 29, 1952)

FOR the guiding field of synchrotrons, fields providing continuous focusing, $1>n>0$, have usually been used. Recently, Courant, Livingston, and Snyder[1] showed that fields which consist of periodic focusing and defocusing regions, $n_1=-n_2\gg1$, have strong focusing properties. We have tried another application of the periodic field. The magnet is divided into guiding magnets and focusing magnets, and the latter are placed in the linear portion of the orbit. Quadrupole or solenoid magnets may be used as focusing magnets.

(A) The stability condition formulated by Courant *et al.* now involves the factor ξ, the ratio of the length of the focusing magnet to π/M, where M = the number of pairs in 2π. Let p_1^2 and p_2^2 be the coefficients of the focusing field in Fig. 1(a). The stability conditionis as follows:

$$|\eta|<1,$$

$$\eta=\cos\frac{\pi}{M}\xi p_1\cos\frac{\pi}{M}\xi p_2+\sin\frac{\pi}{M}\xi p_1\sin\frac{\pi}{M}\xi p_2\left[\left\{\frac{\pi}{M}(1-\xi)\right\}^2 p_1p_2-\frac{p_1^2+p_2^2}{p_1p_2}\right]\frac{1}{2}-\frac{\pi}{M}(1-\xi)\left\{p_1\sin\frac{\pi}{M}\xi p_1\cos\frac{\pi}{M}\xi p_2+p_2\cos\frac{\pi}{M}\xi p_1\sin\frac{\pi}{M}\xi p_2\right\}. \quad (1)$$

Figure 1(b) shows the first stable region.

The quadrupole field shown in Fig. 2 increases linearly with x near the center. This field provides focusing and defocusing force in the x and z directions, respectively, and the forces are given by the equivalent n_{eq} and $-n_{eq}$, respectively, where,

$$n_{eq}=(H'/H_0)R. \quad (2)$$

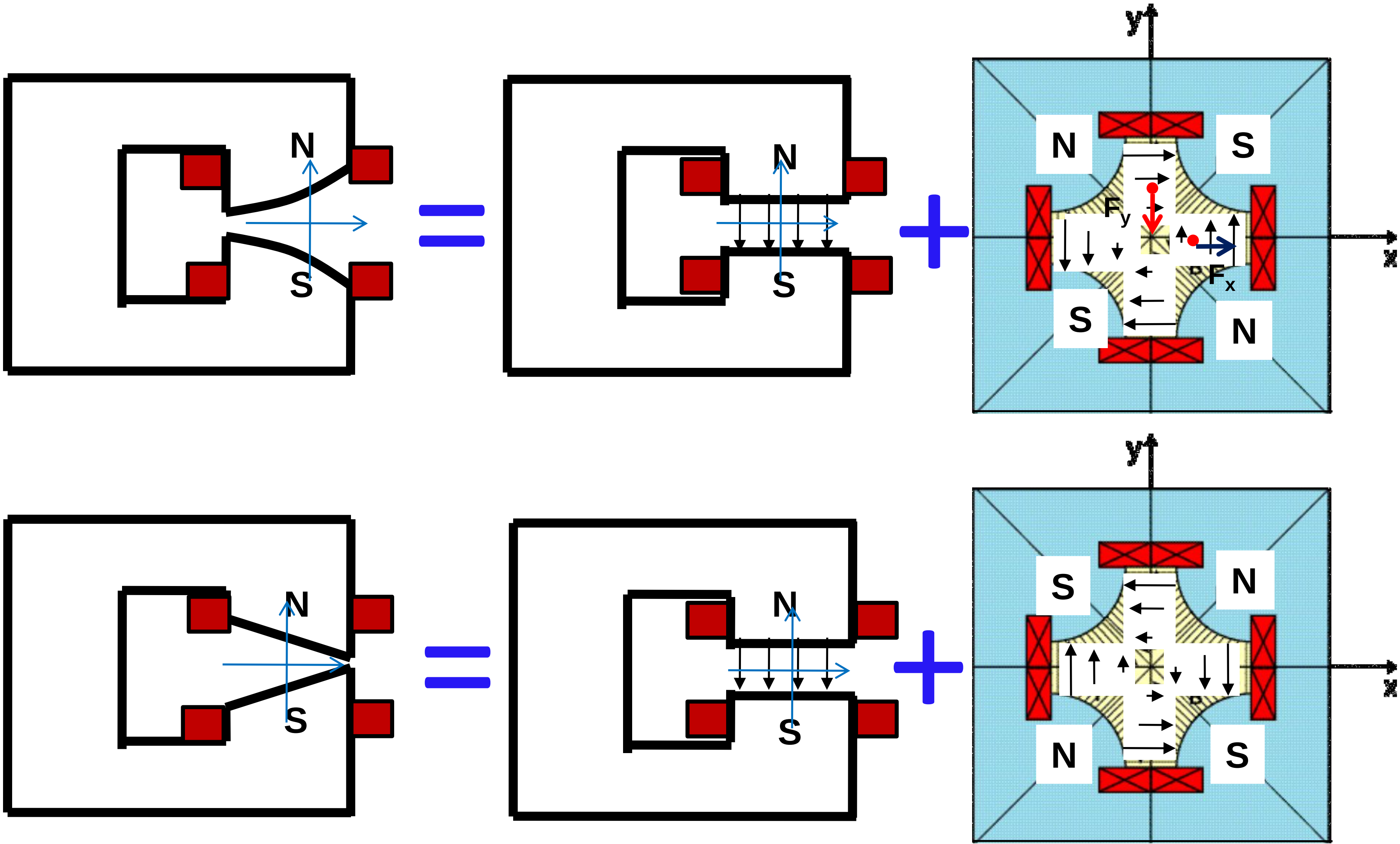
R = the radius of the orbit in the guiding field, H_0 = the guiding

Strong Focusing Synchrotron (1): Separate-function type

Combined function magnet

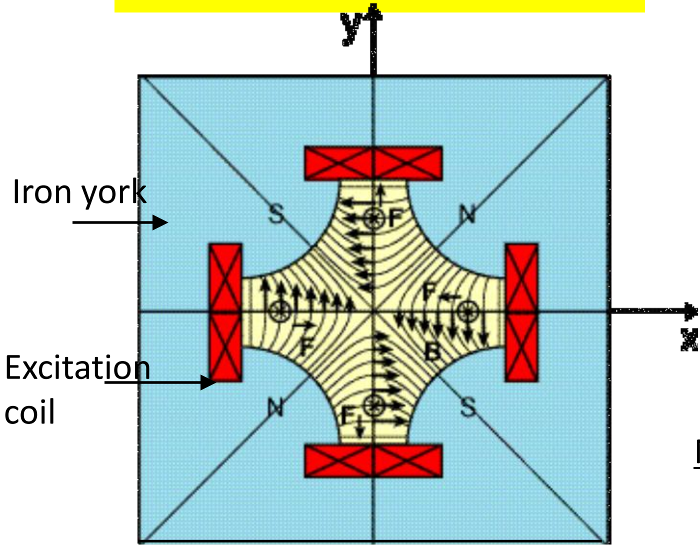
Bending magnet with a function of bending

Quadrupole magnet with functions of focusing and defocusing



Strong Focusing Synchrotron (2): Lattice

Quadrupole magnet for focusing and defocusing



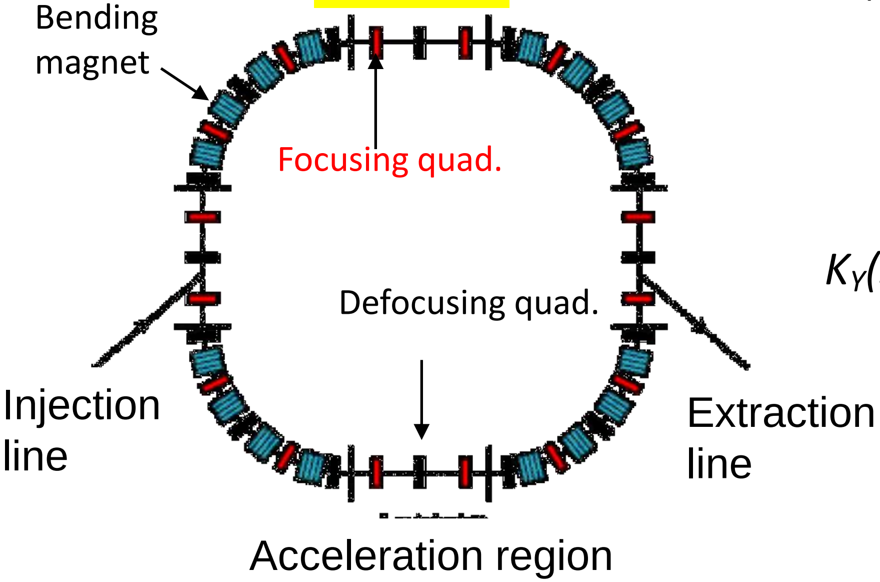
Let think about a magnet system consisting of bending magnet and focusing/defocusing magnet. ➡ Lattice

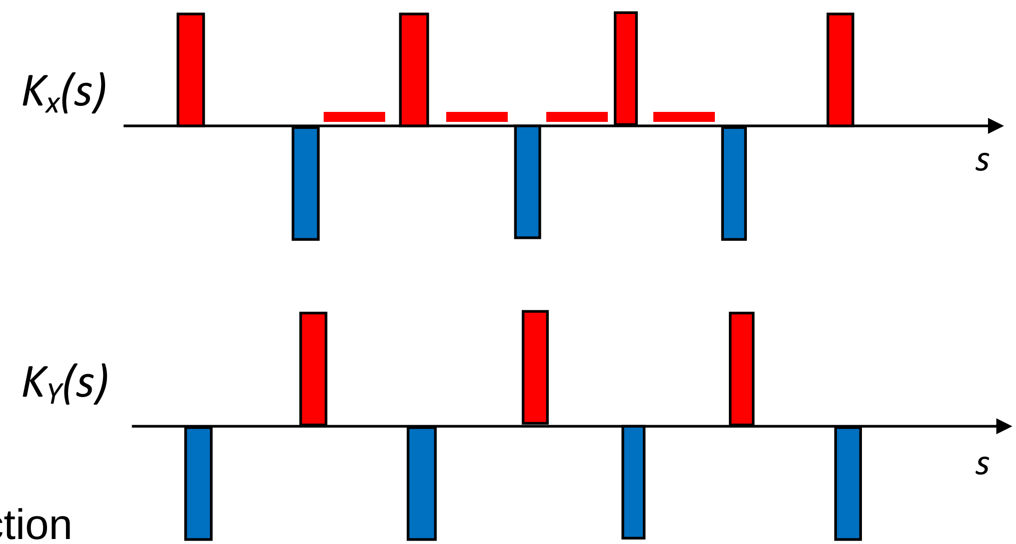
Equation of motion: Betatron equation

$$\begin{cases} \dfrac{d^2x}{ds^2} + K_x(s)x = 0 \\ \dfrac{d^2y}{ds^2} + K_y(s)y = 0 \end{cases}, \quad \text{where} \begin{cases} K_x(s) = \dfrac{1}{\rho^2} - \dfrac{1}{B_0\rho}\dfrac{\partial B_y(0,0)}{\partial x} \\ K_y(s) = \dfrac{1}{B_0\rho}\dfrac{\partial B_y(0,0)}{\partial x} \end{cases}$$

Note: *Coefficients of restoring force are a functions of orbit coordinate s.*

Lattice

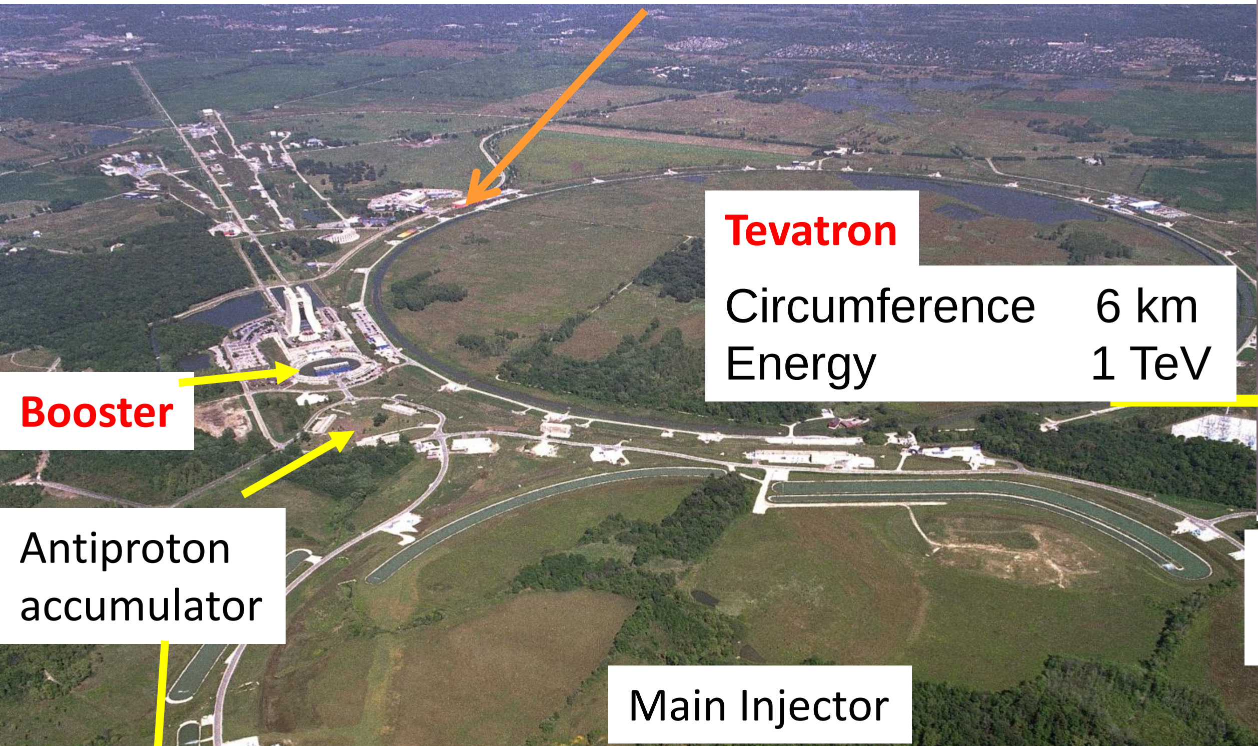




New Injector (FNAL)

50 km west Chicago

B0 Detector



Tevatron

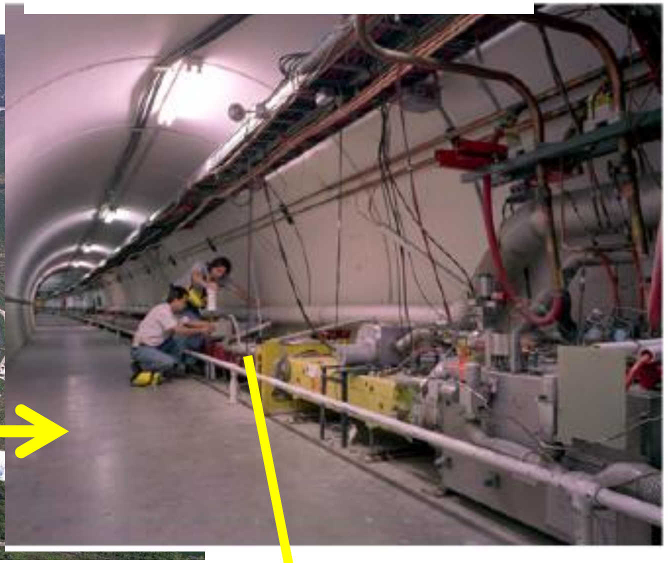
Circumference	6 km
Energy	1 TeV

Booster

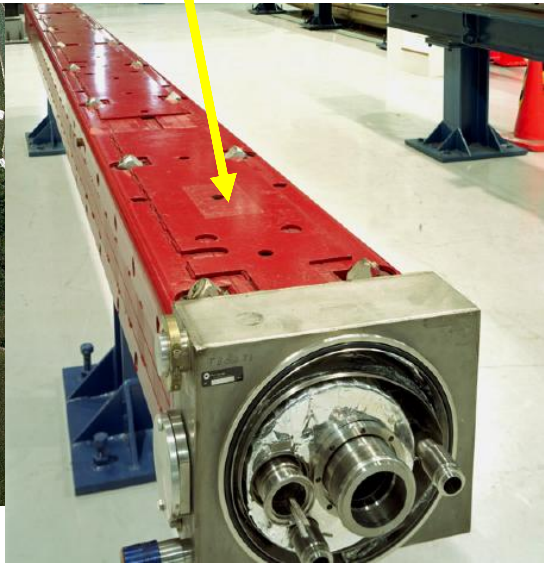
Antiproton accumulator

Main Injector

Tevatron accel. tunnel



4.5 Tesla Superconducting magenet

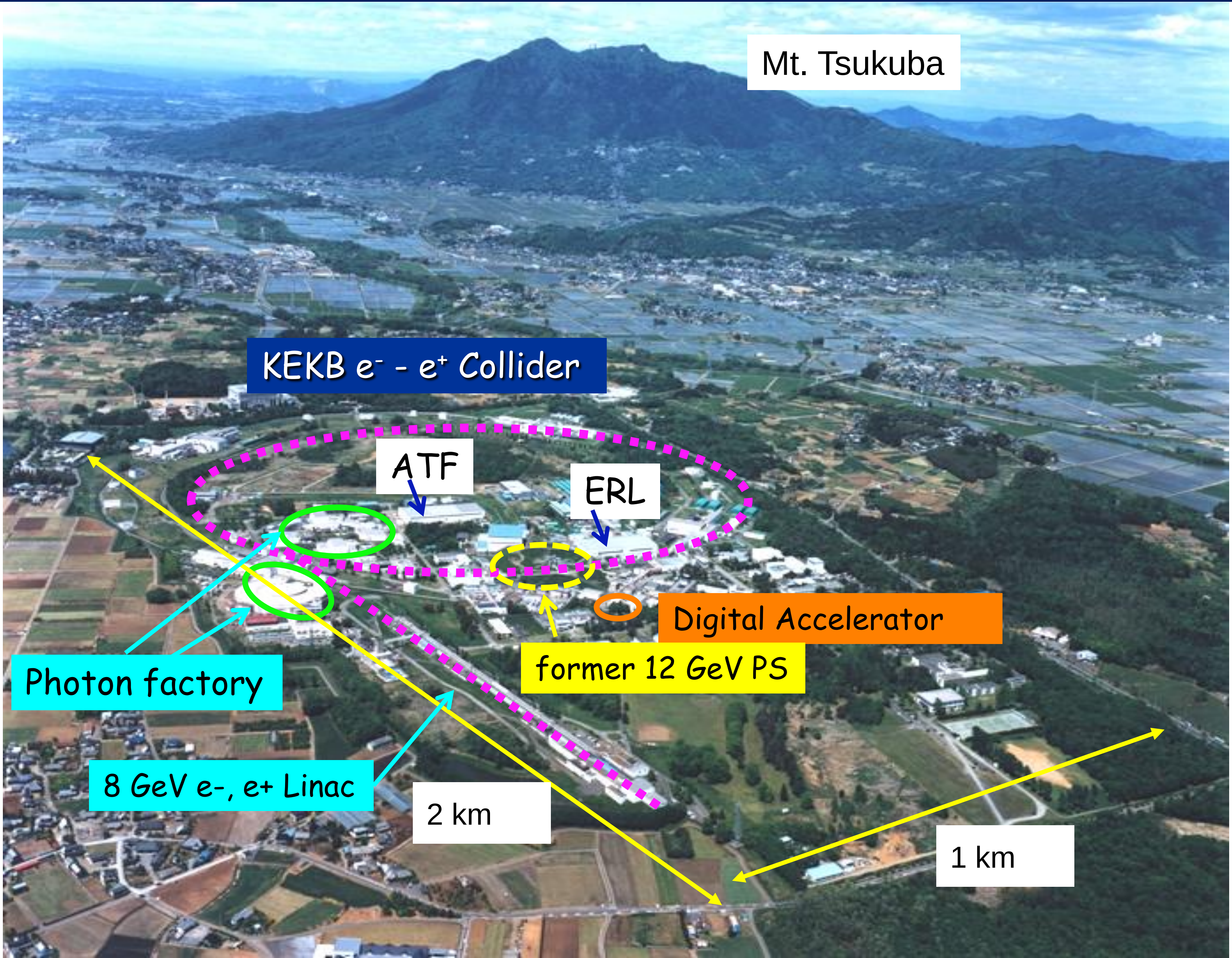


Relativistic Heavy Ion Collider (BNL)

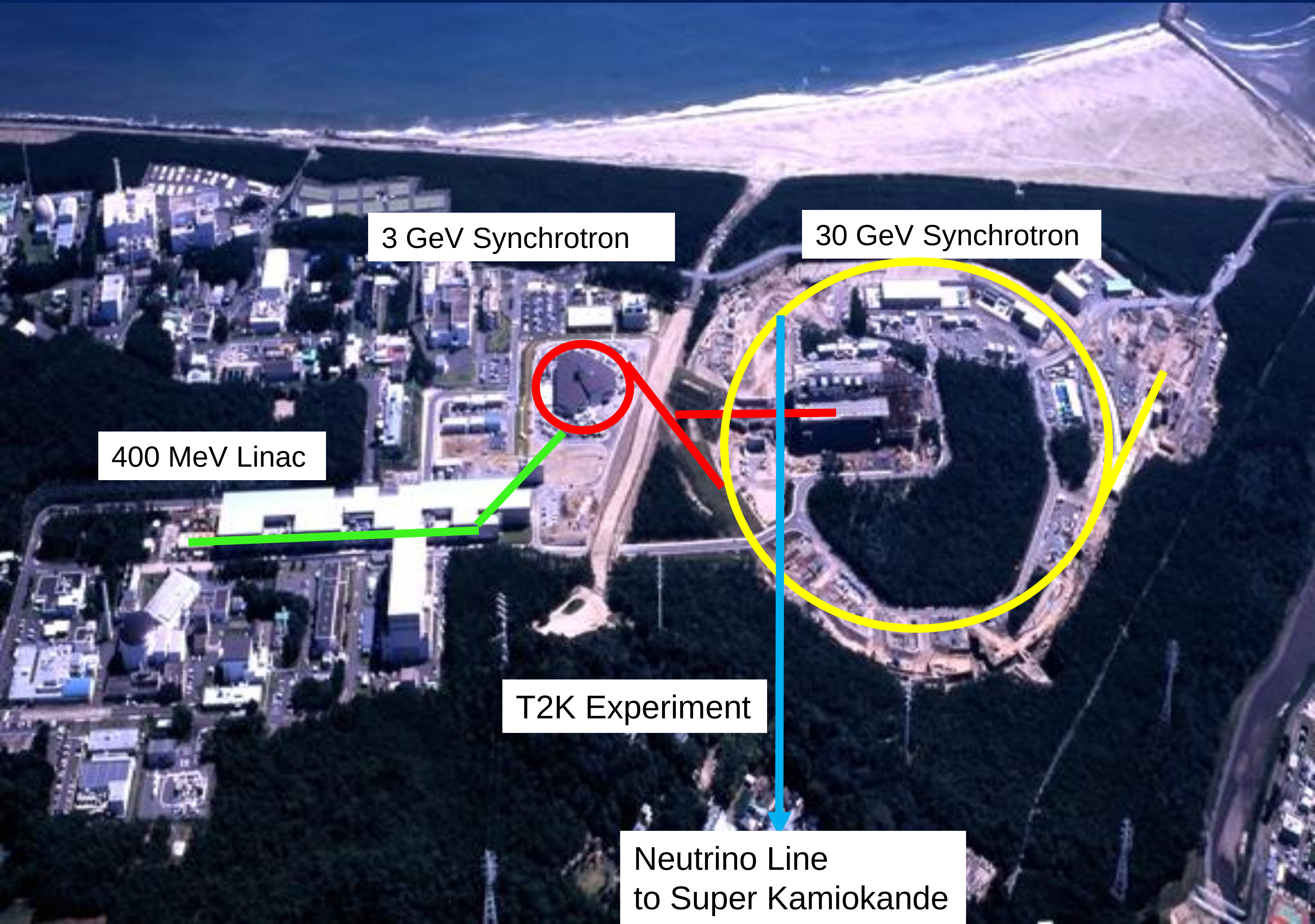
1 in 1 3.45 T superconducting magnet

RF in the colliding mode

KEK Tsukuba Campus

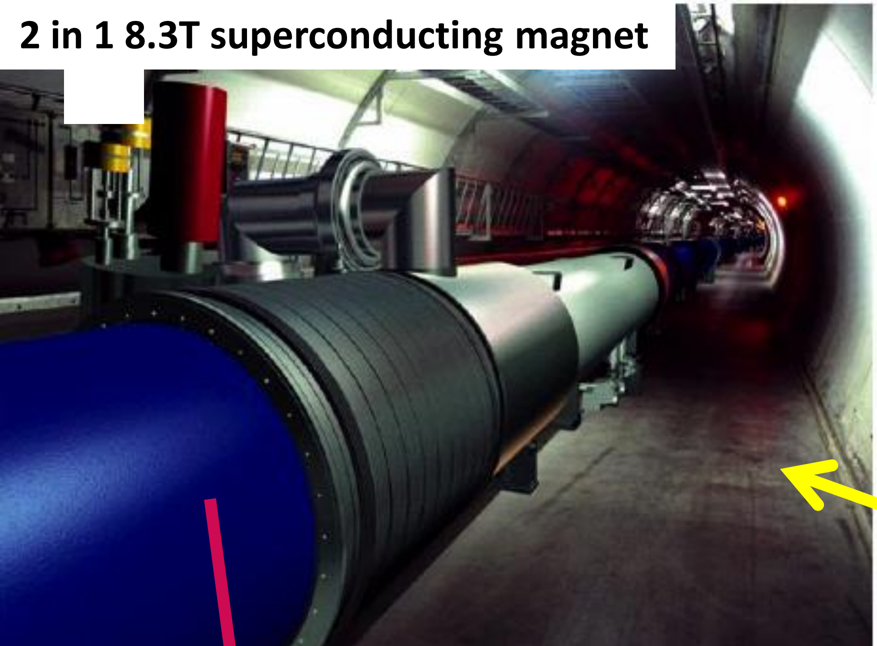


High Intensity Proton Driver (J-PARC, KEK Tokai Capus)

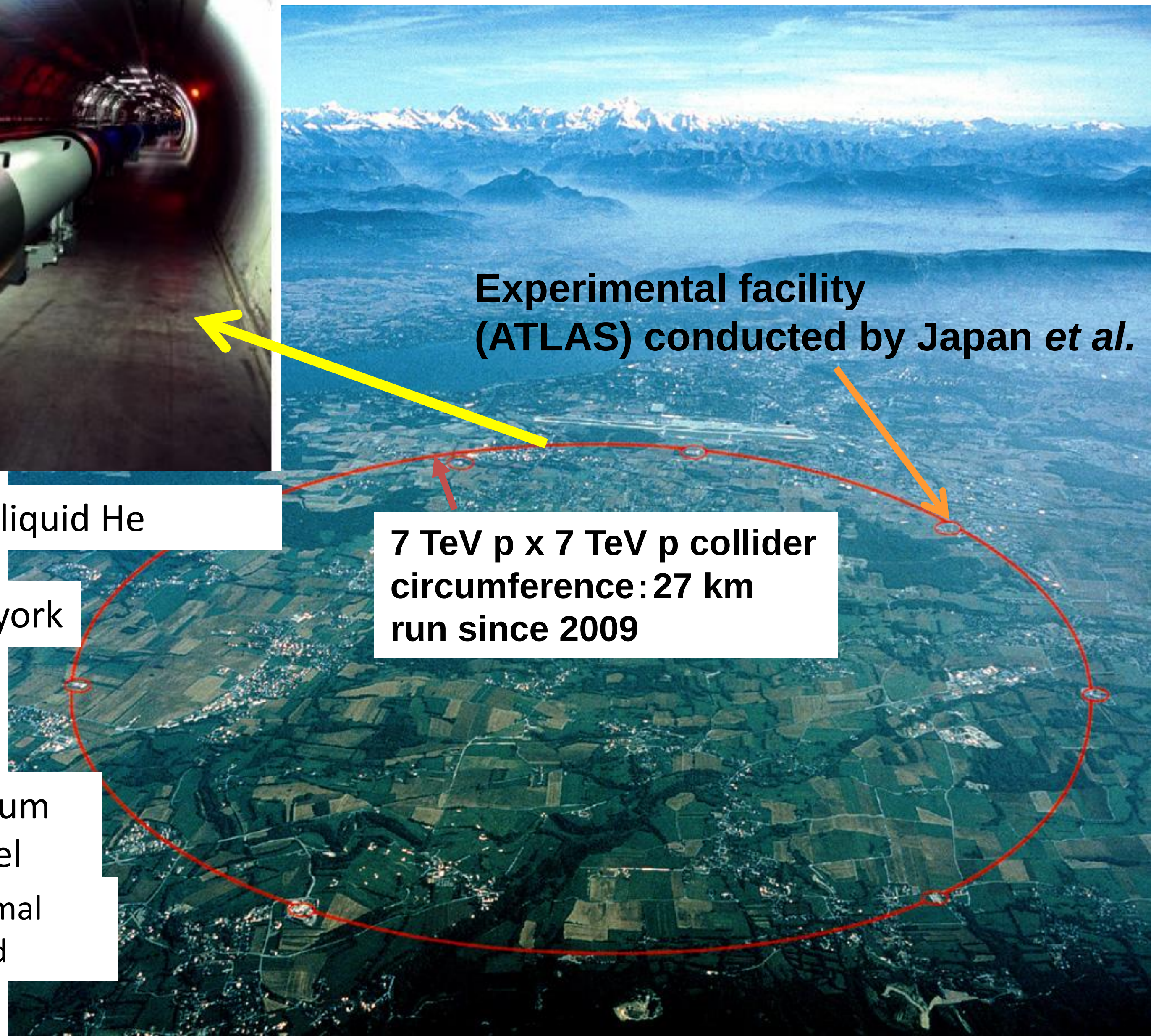


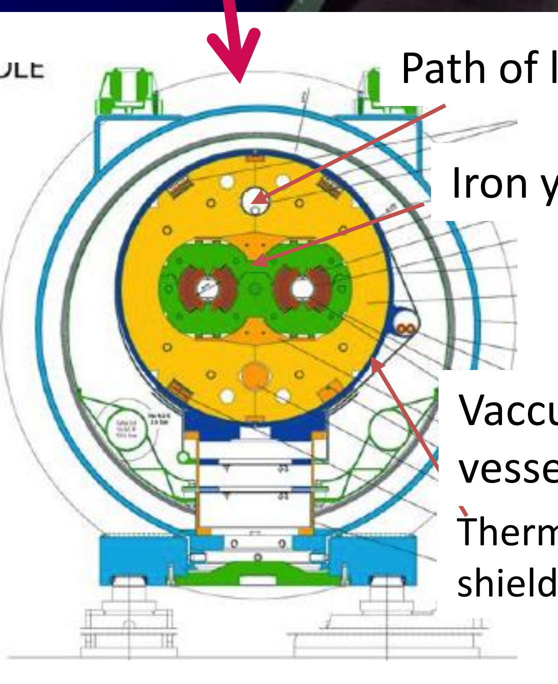
LHC (CERN)

2 in 1 8.3T superconducting magnet



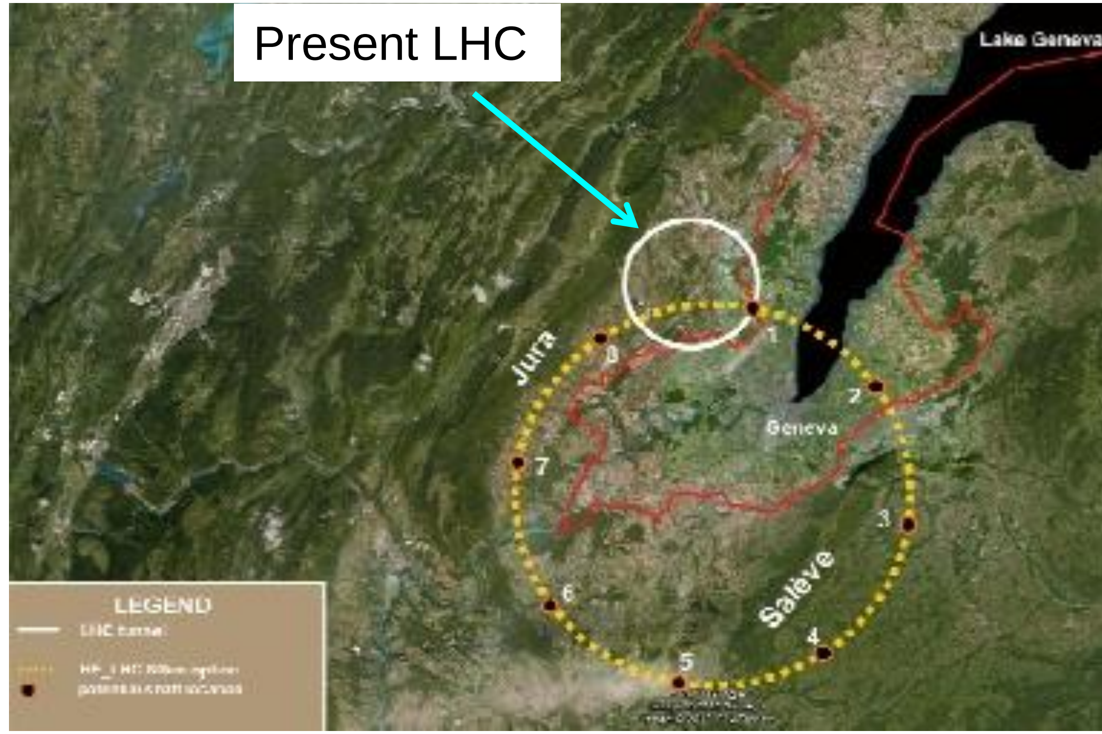
Large Hadron Collider (LHC)

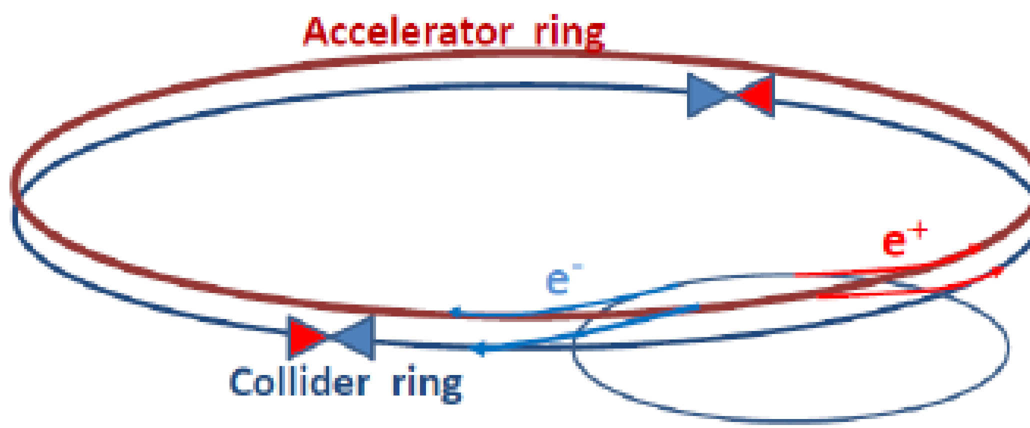




TLEP and Super High Energy LHC in the same tunnel

Circumference of ring : 80 km
350 GeV e^+ x 350 GeV e^- Collider
100 TeV p x 100 TeV p Collider
Luminosity: 5 x 10^{34} $cm^{-2}sec^{-1}$
2x10^6 Higgs /5 years

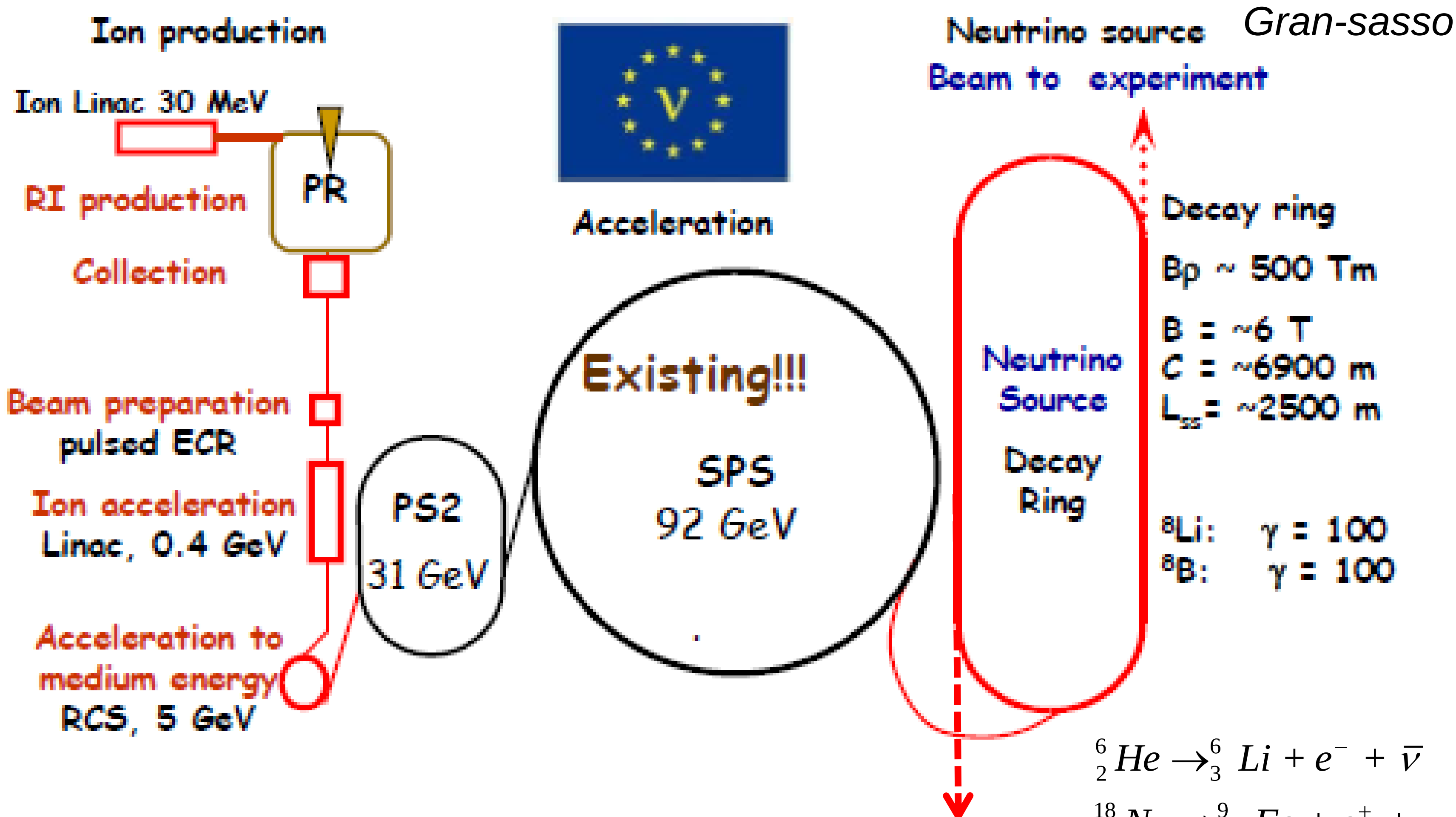




- ➢ International design team has started their tasks.

Neutrino Factory: CERN Scenario

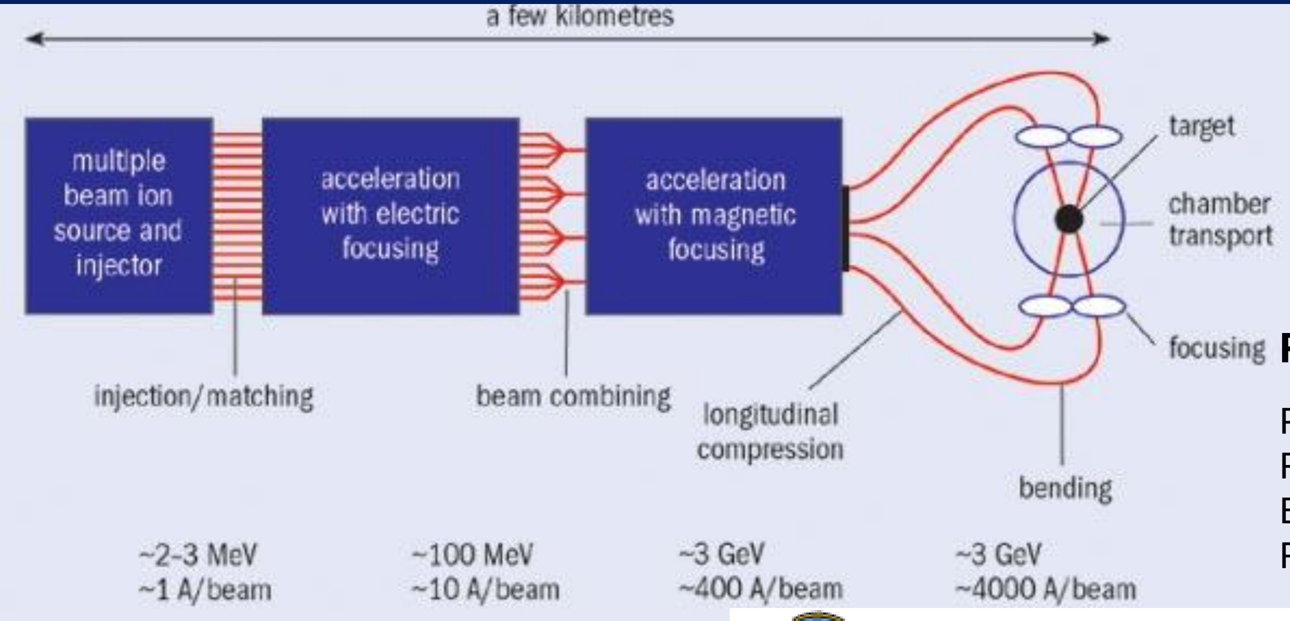
Beta Beam scenario EUROnu



$$^{6}_{2}He \rightarrow ^{6}_{3}Li + e^{-} + \overline{\nu}$$

$$^{18}_{10}N_{e} \rightarrow ^{9}_{18}Fe + e^{+} + \nu$$

Heavy Ion Inertial Fusion Drivers



US Design based on Induction Linac

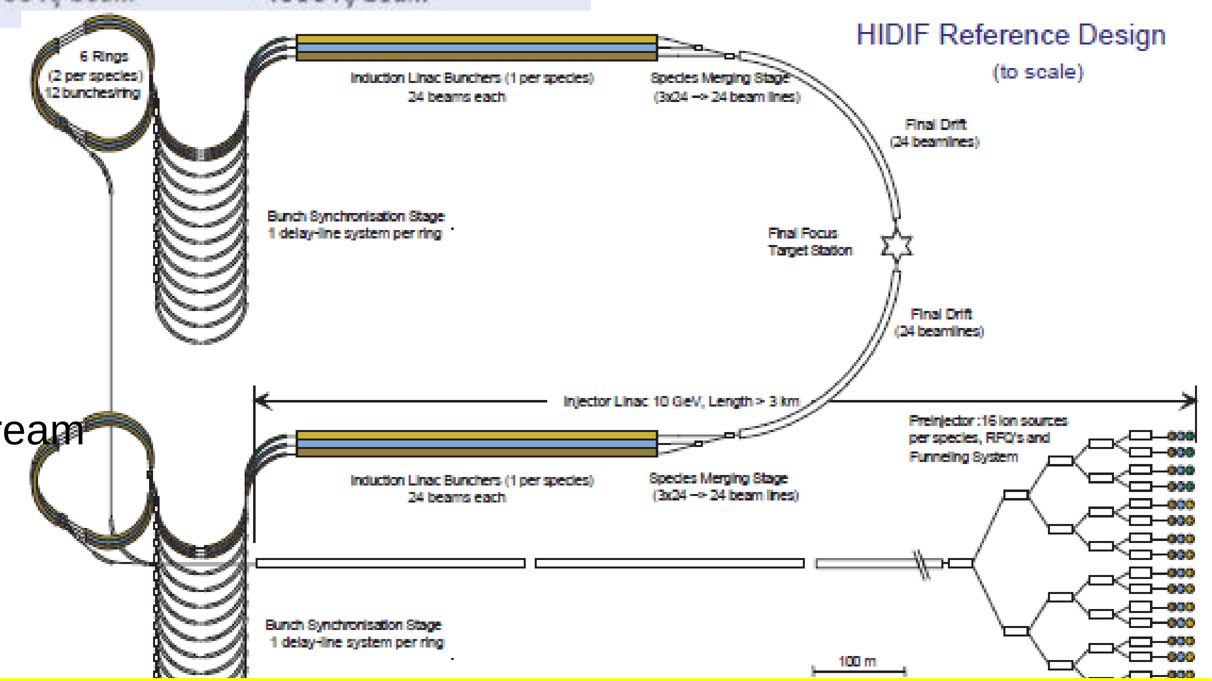
Requirements of driving beam:

Pulse length ~ 10 nsec
Range on target material 0.1 – 1 mm
Beam power 1 MJ
Rep-rate 1-10 Hz

Solution:

- ➢low charge state
- ➢large mass number
- ➢large intensity

U1+ etc.
Combinning of many beams downstream



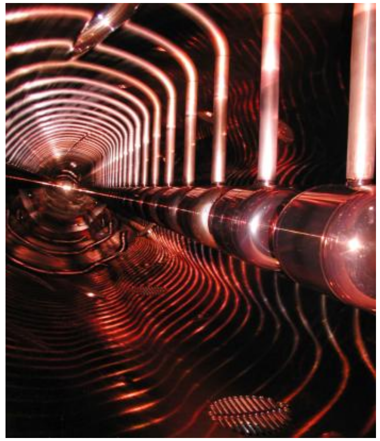
EU Design based on RF Accelerators

Partial success of I.F. => rather induce tone-down of I.F. itself in US

Drivers to obtain Swift Heavy Ions for Various Applications

1. ES Accelerator (1931-)

2. RF Linac (1945-)



3. Cyclotron (1931-)

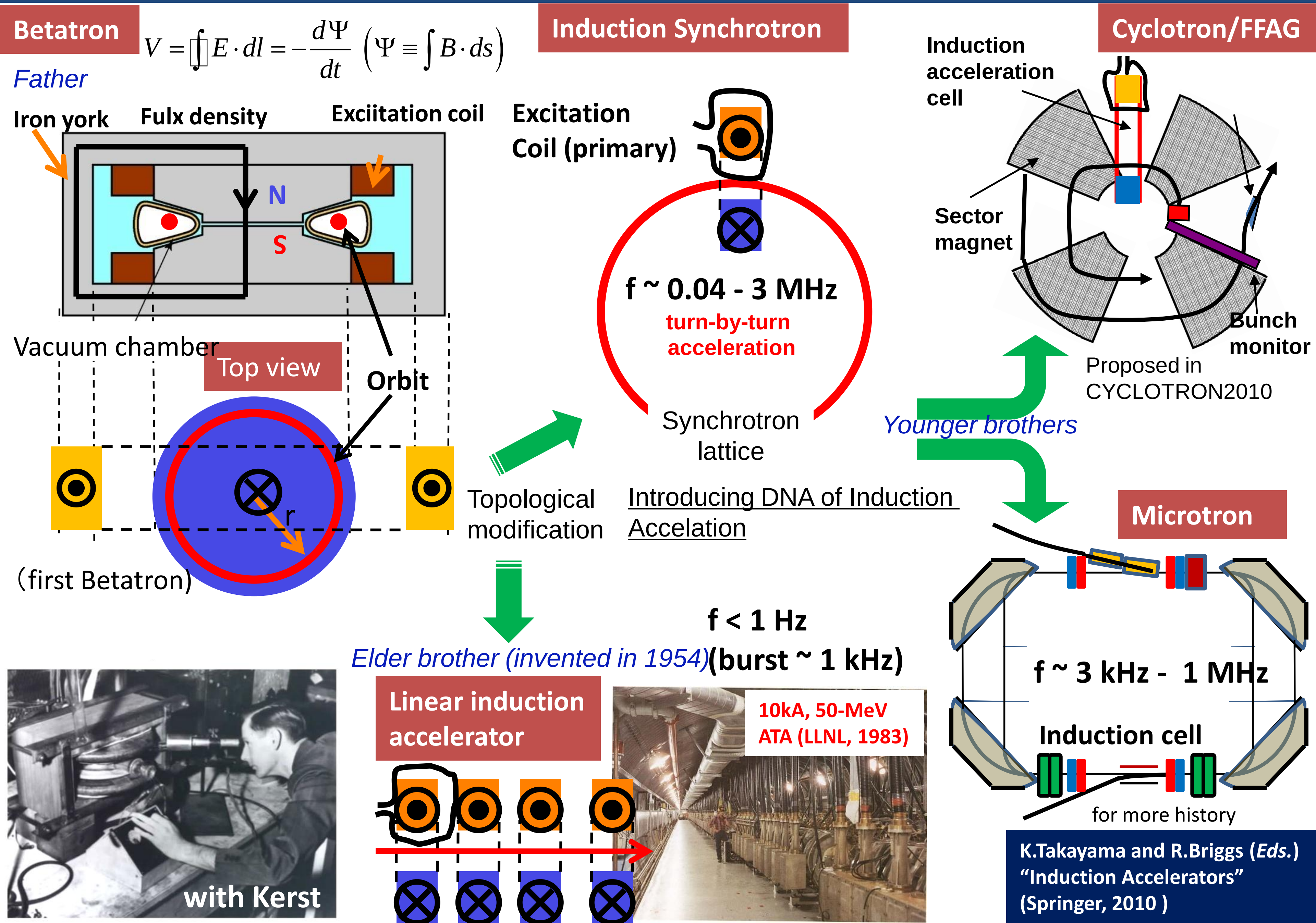
4. Synchrotron (1945-)

Existing driver

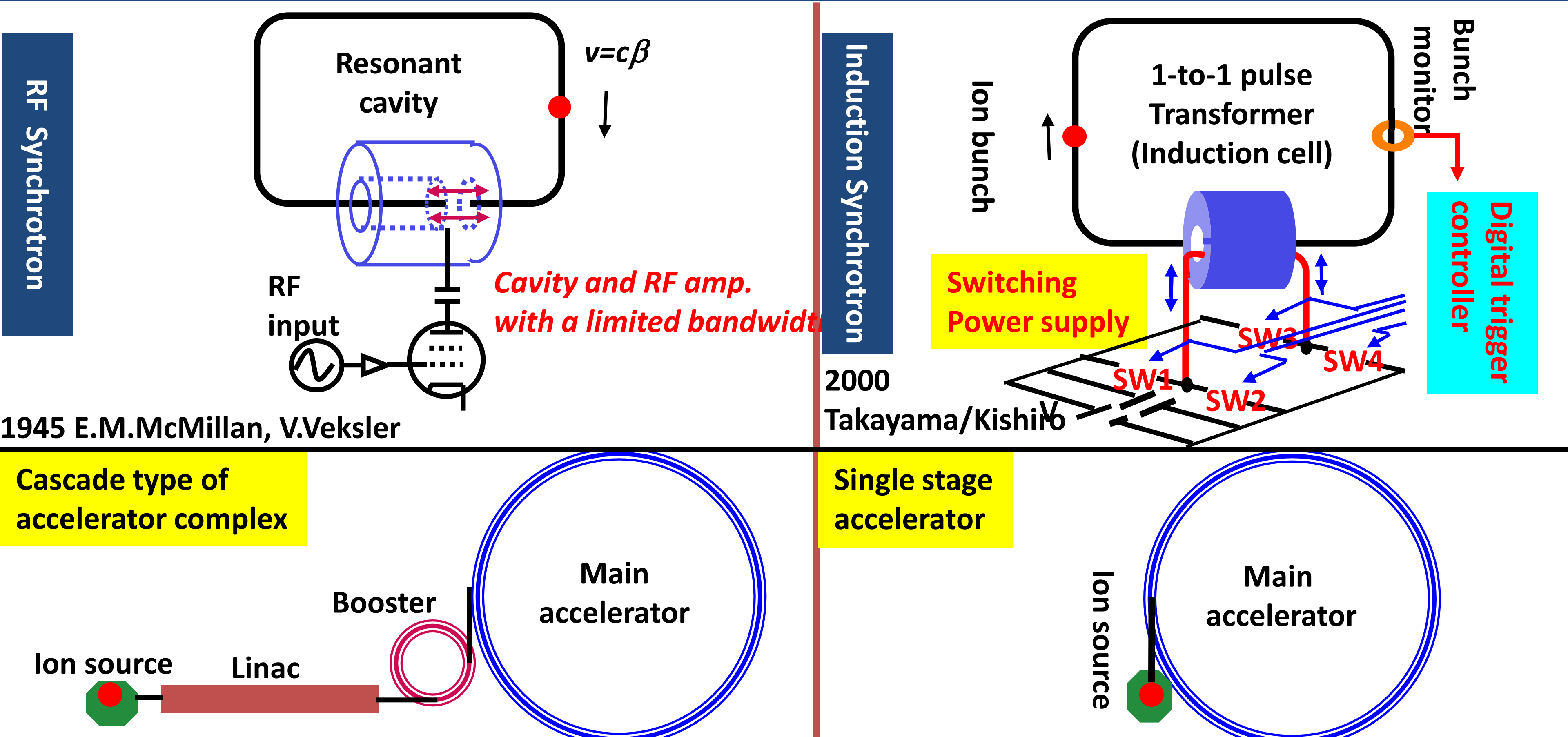
Recently Deve-loped driver

Type	Advantage	Disadvantage
Electrostatic Accelerator (Tandem at Orsay, IUAC)	Any ion species	Energy limited due to discharge
RF Linac	A lot of experience Easy beam extraction	*A/Q* limited Expensive for high energy
RF Cyclotron (low, medium energy)	DC beam available Wide range of ion species	*A/Q* limited
RF Synchrotron (medium energy)	Extremely high energy obtainable	*A/Q* limited Large scale injector required Expensive
•Induction Synchrotron (Digital Accelerator) •Induction Microtron	Any ion species *A/Q* no limited (e.g. U^{1+}) Large scale injector not required	Beam intensity limited (due to low energy injection)

From Betatron to Induction Synchrotron / Cyclotron/Microtron

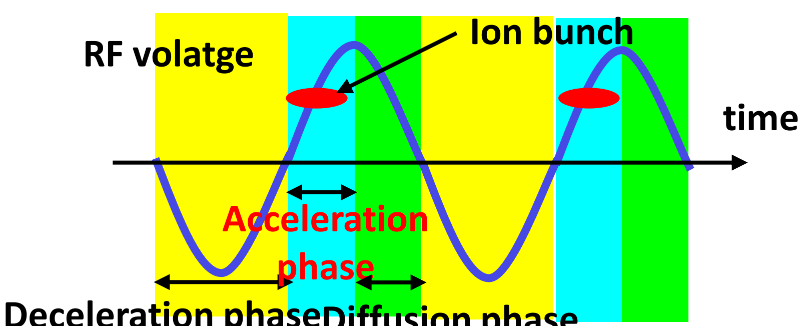


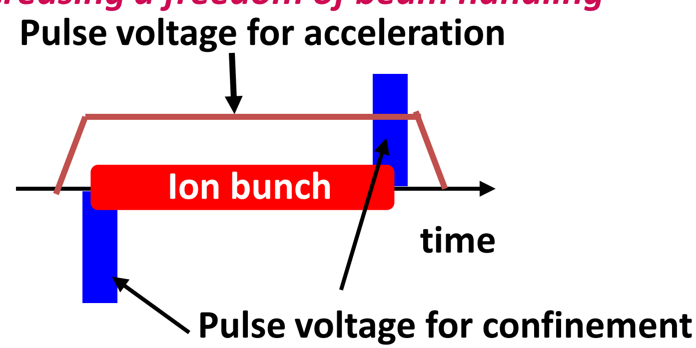
Difference between RF Synchrotron and Induction Synchrotron



Functionally combined acceleration/confinement -> increase in the local density -> limit on a beam current

Functionally separated acceleration/confinement -> increasing a freedom of beam handling



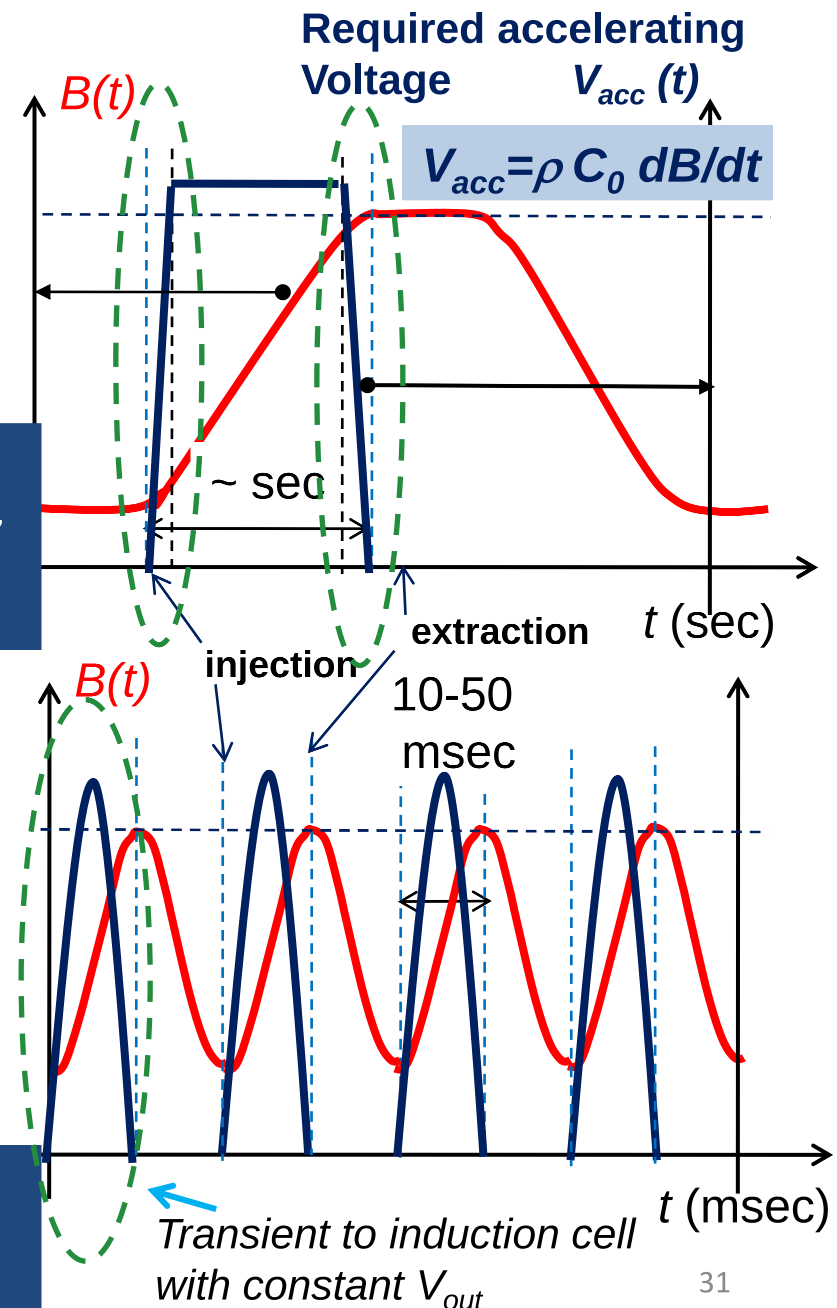


Demonstration of two types of Induction Synchrotron

(1) Slow cycling induction synchrotron
in 2006
KEK 12 GeV Proton Synchrotron
where Guiding fields are excited by pattern control power supply

0.25 – 1.5 T

K.Takayama, K.Koseki , S.Igarashi, T.Iwashita, J.Kishiro, M.Shirakata, T.Toyama, M.Watanabe *et al.*, *Phys. Rev. Lett.* **94**, 144801 (2005)
K.Takayama *et al.*, *Phys. Rev. Lett.* **98**, 054801(2007)

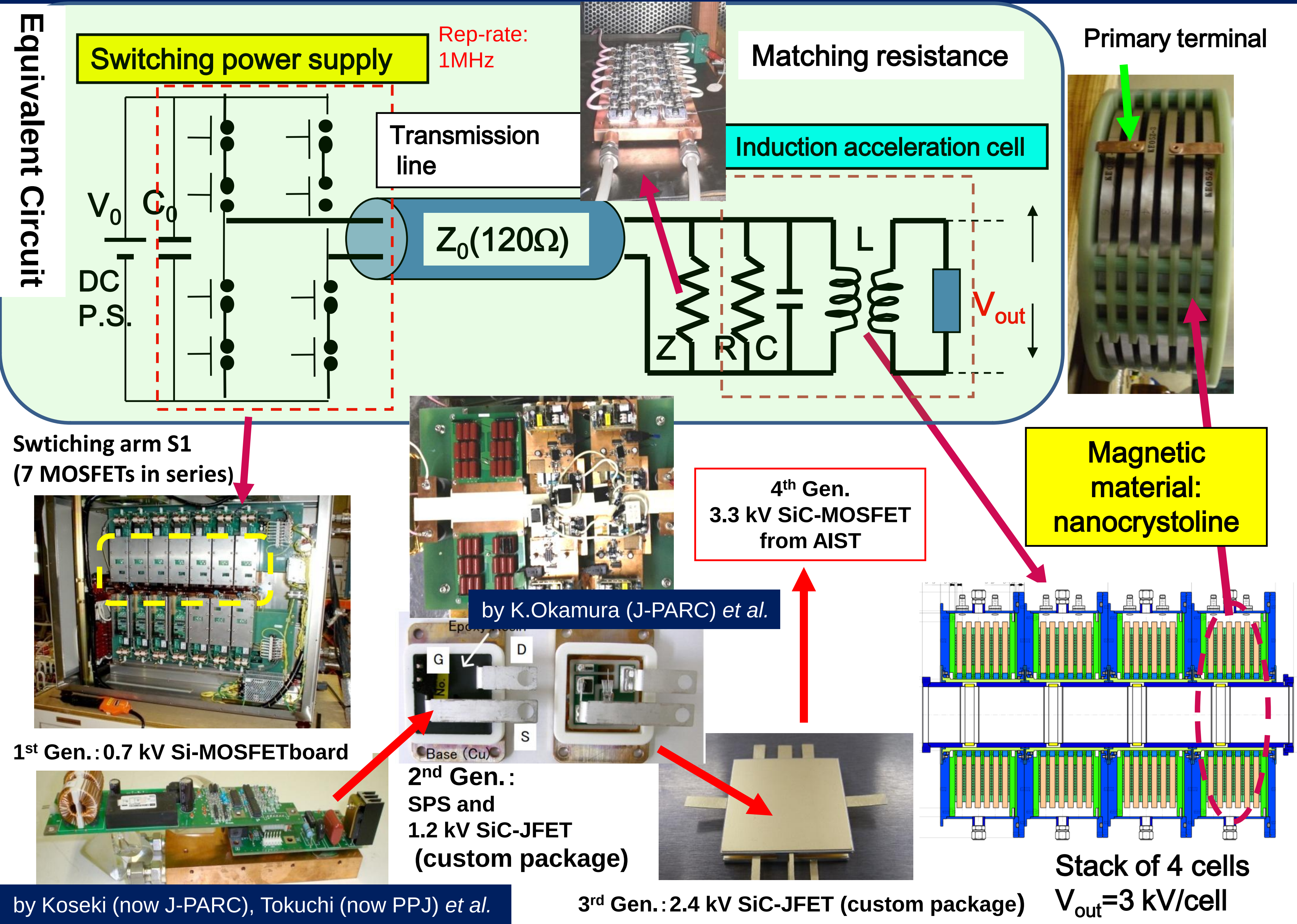


(2) Fast cycling induction synchrotron
in 2013
KEK Digital accelerator
where Guiding fields are excited by resonant circuit

0.039 -0.84 T

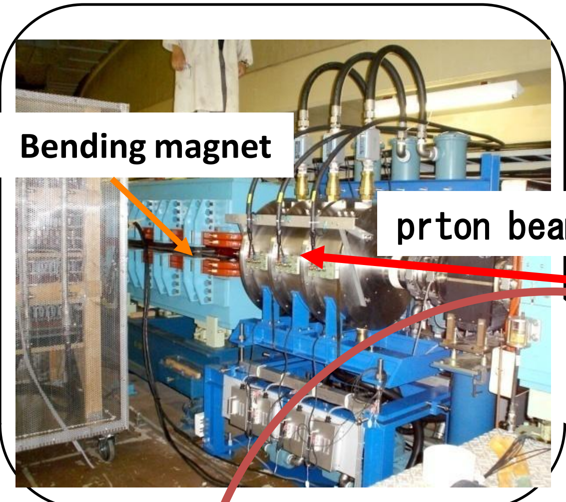
T.Iwashita, K.Takayama *et al.*, "KEK Digital Accelerator", Phys. Rev. ST-AB 14, 071301 (2011)
K.Takayama *et al.*, *Phys. Rev.* ST-AB 17, 010101 (2014)

Heart of Digital Accelerator : Evolutional Induction Accelerator System



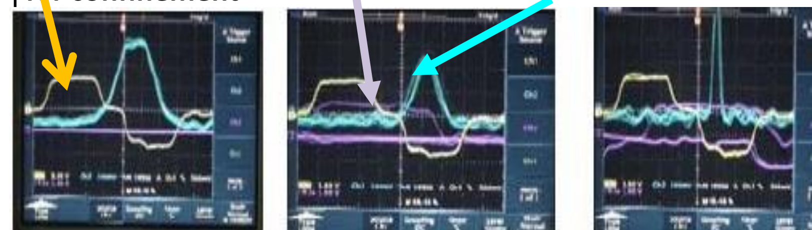
Complete Demonstration of the Induction Synchrotron Concept (2006, March)

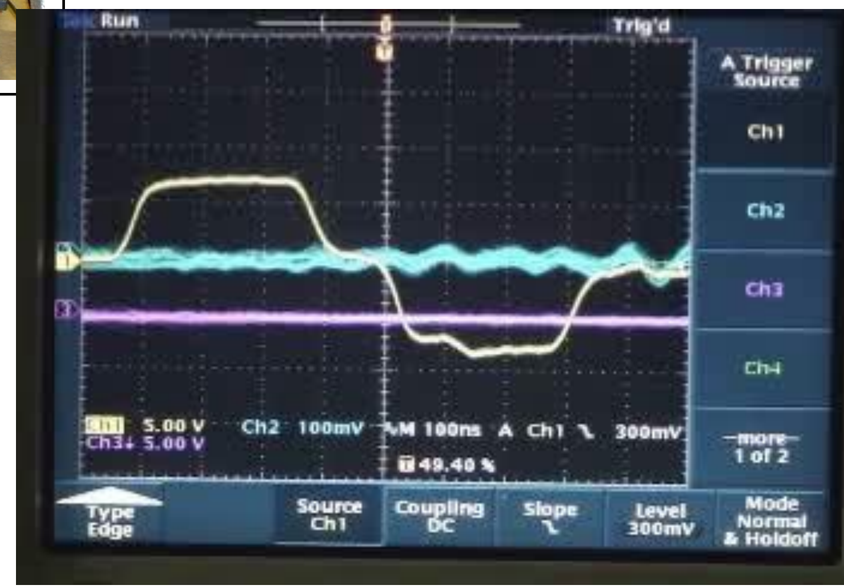
ion : H^+
500 MeV -> 6 GeV
$N=2.5 \times 10^{11}$

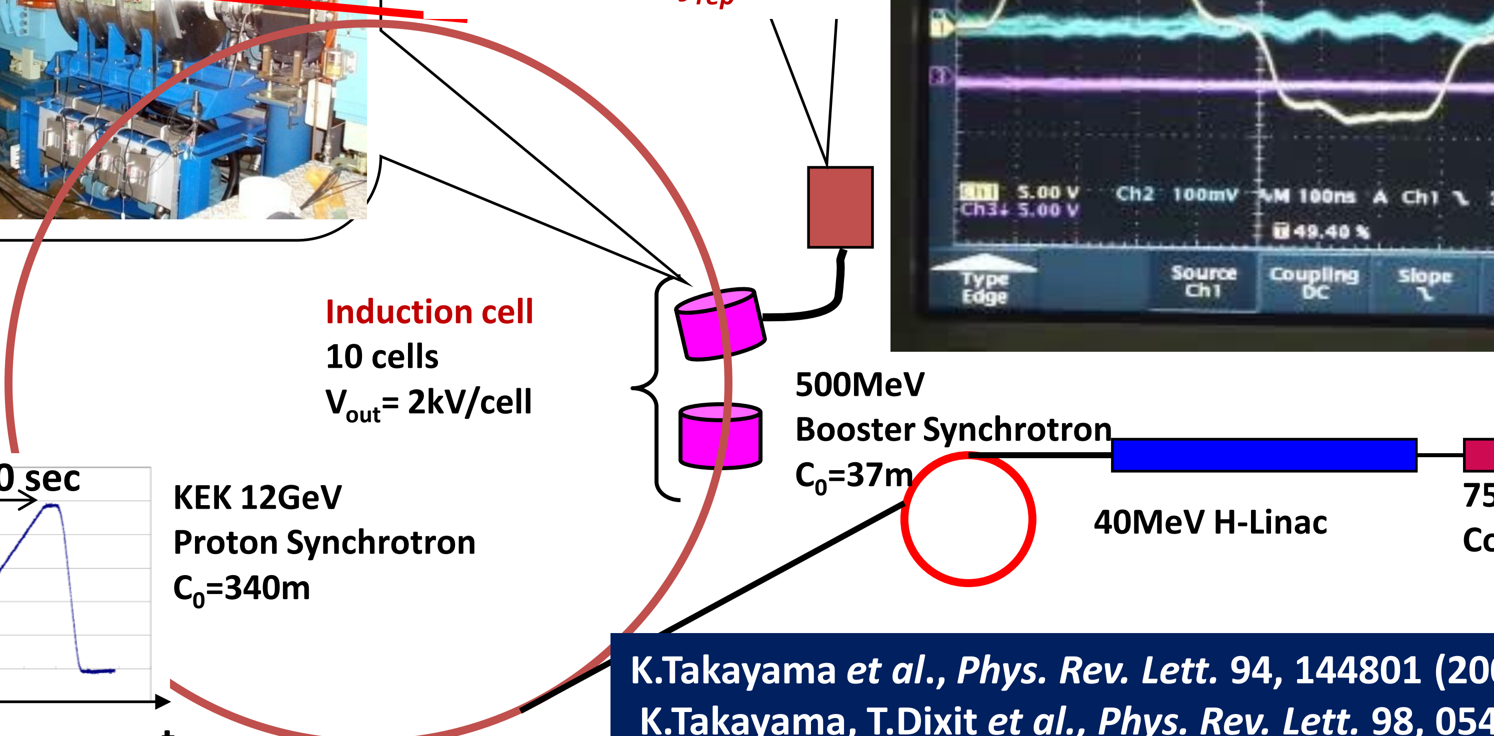


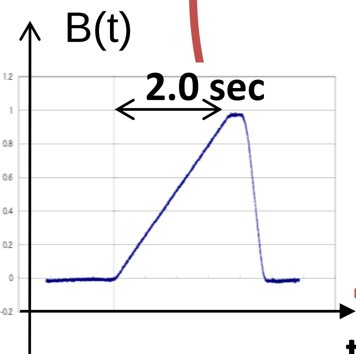
Switching Power Supply
(40kW、Max f_{rep}=1MHz)

500 MeV → 6 GeV









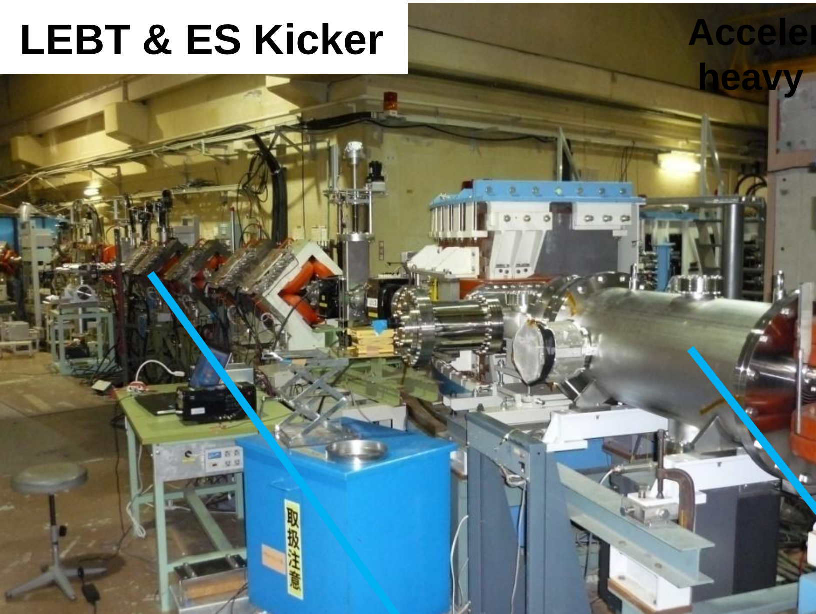
K.Takayama *et al.*, *Phys. Rev. Lett.* 94, 144801 (2005)
K.Takayama, T.Dixit *et al.*, *Phys. Rev. Lett.* 98, 054801 (2007)

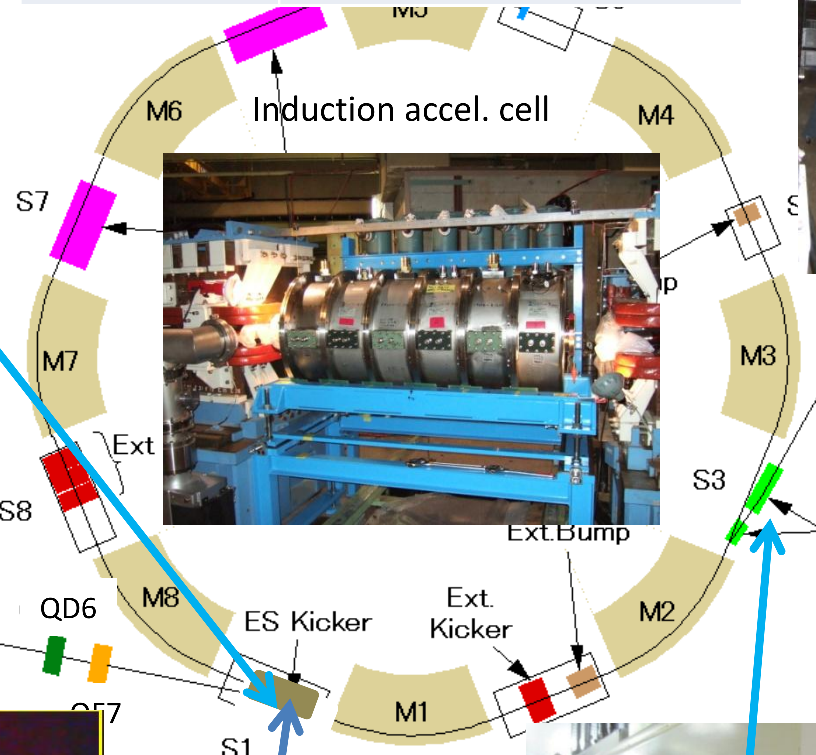
KEK Digital Accelerator (Fast Cycling Induction Synchrotron)

T. Iwashita *et al.*, *"KEK Digital Accelerator", Phys. Rev. ST-AB 14, 071301 (2011).*

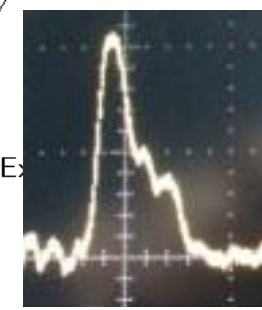
Circumference	37.7 m
B_{mx}	0.84 Tesla
Mximum energy	315 MeV (p), 2.15 GeV（Gold）

LEBT & ES Kicker

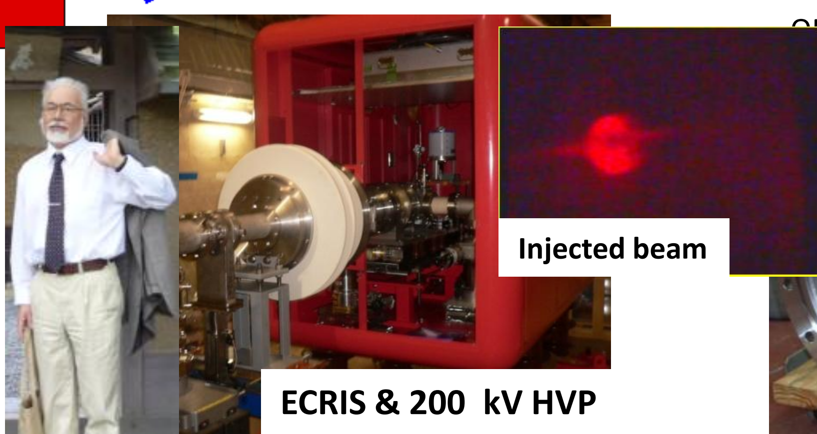




Extracted beam

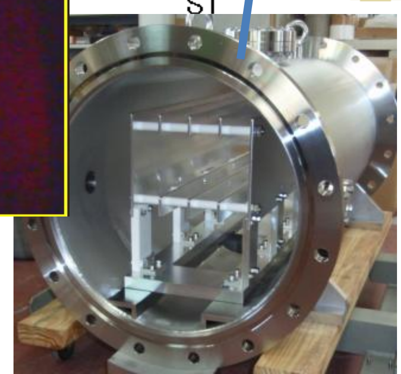


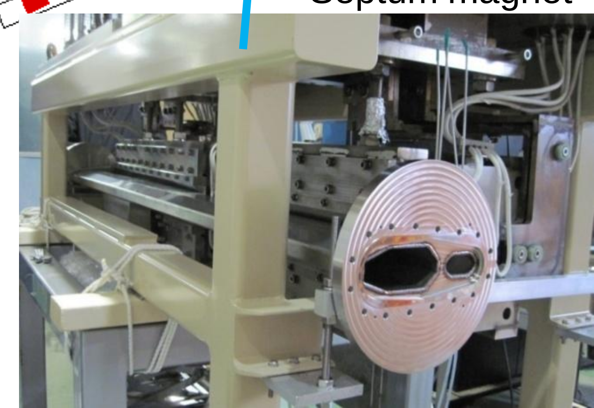
Septum magnet



Injected beam

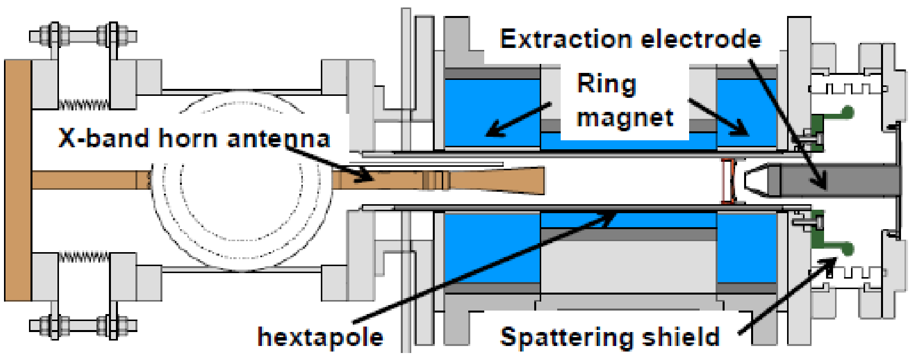
ECRIS & 200 kV HVP



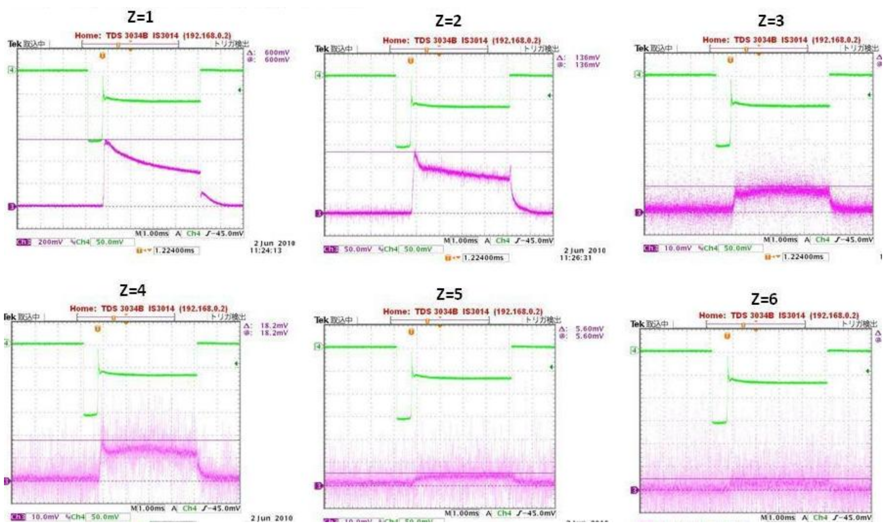


Ion Source (present and near future)

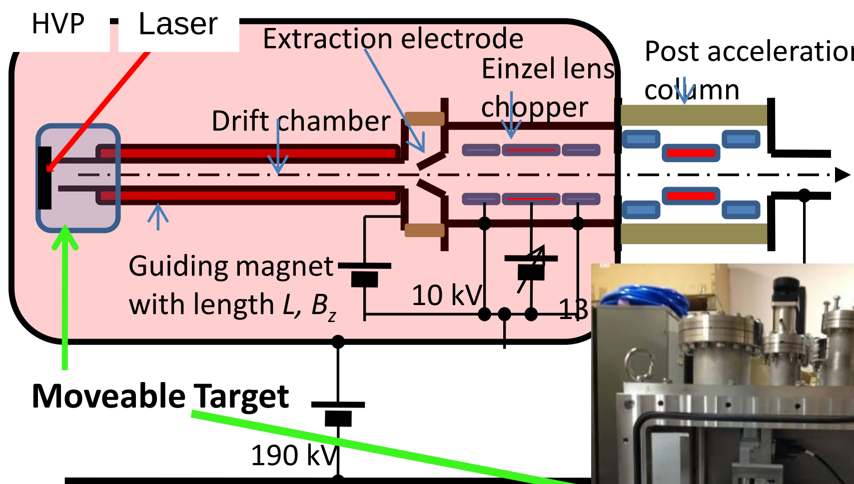
Present ion source (ECRIS) for Gaseous ions

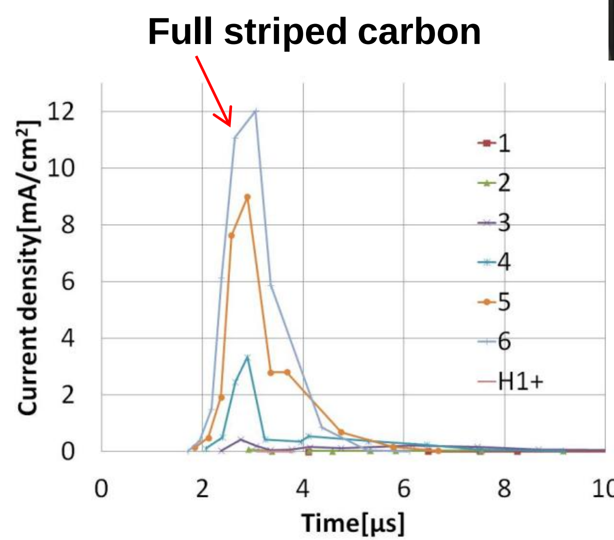


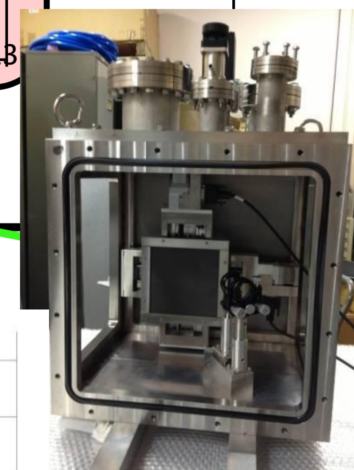
Ne Ion Pulse



LAIS for full stripped C and metal ions



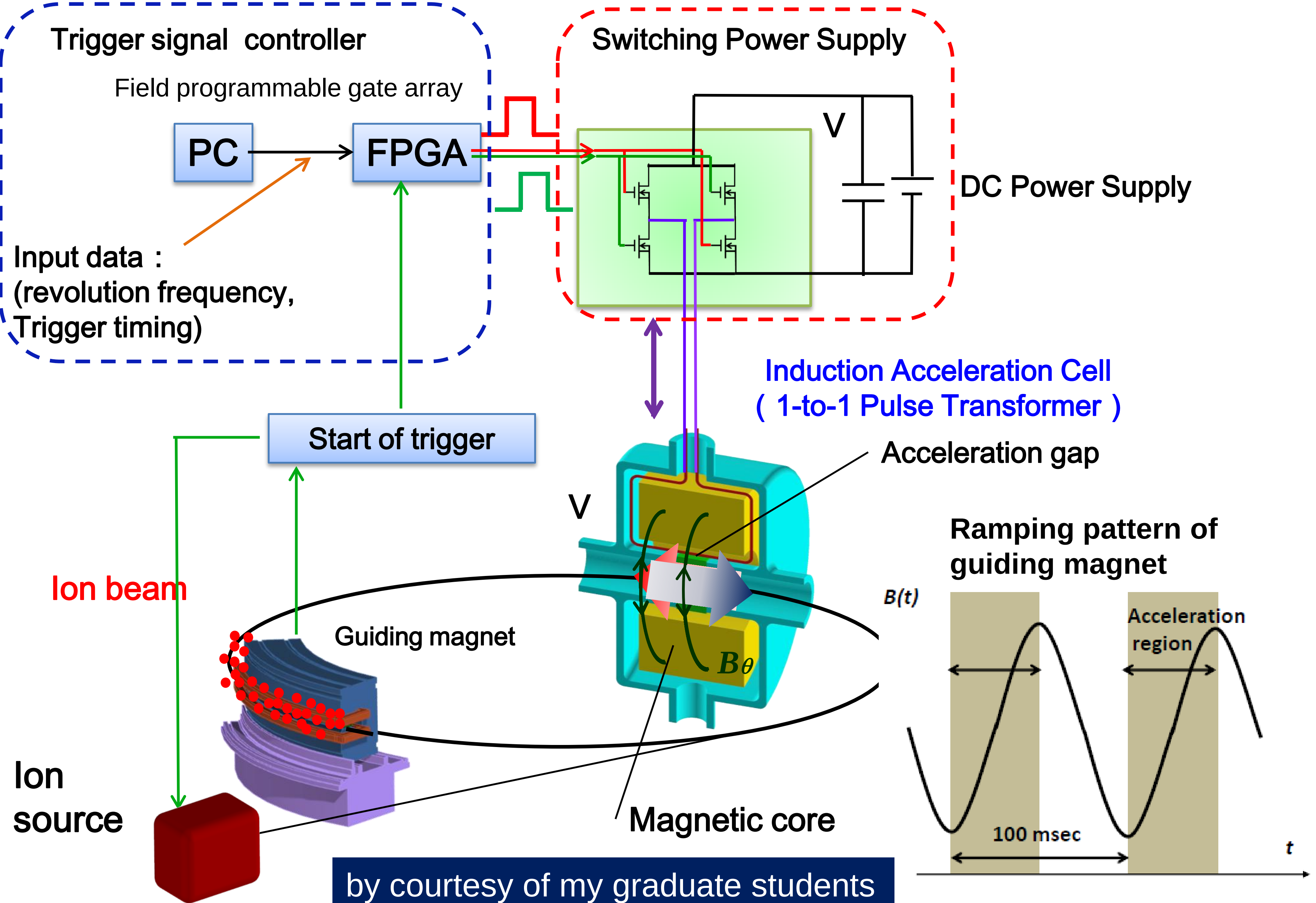




Ion source	Expected ion	Energy	Particle number/sec
ECR Ion Source	H, He, C, N, O, Ne, Ar	< 140 Me V/au, 200MeV	$<10^{10}$
Laser Ablation Ion Source	Xe, Al, Fe, Cu, Ag, Au	< 70 MeV/au	$< 10^{9}$

N. Munemoto *et al.*
R.S.I. 85, 02B922 (2014)

More Realistic Operational Layout of KEK Digital Accelerator

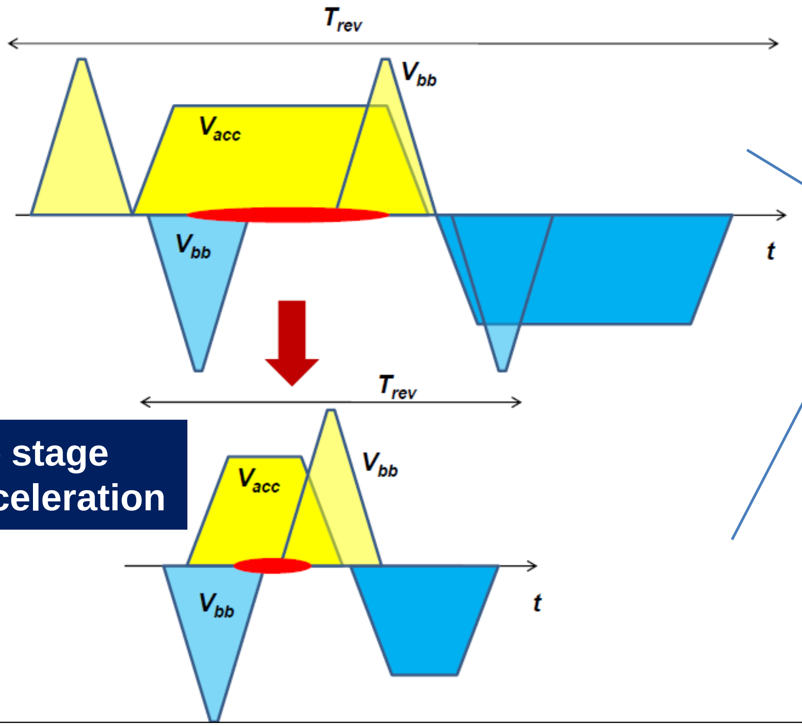


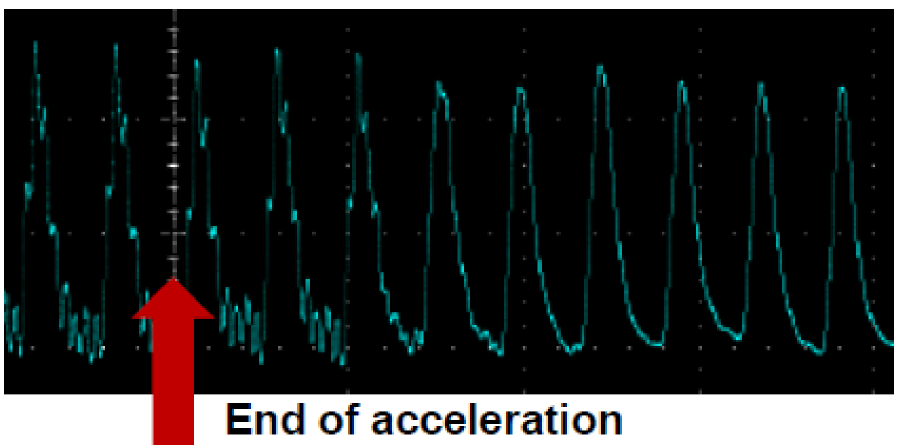
by courtesy of my graduate students

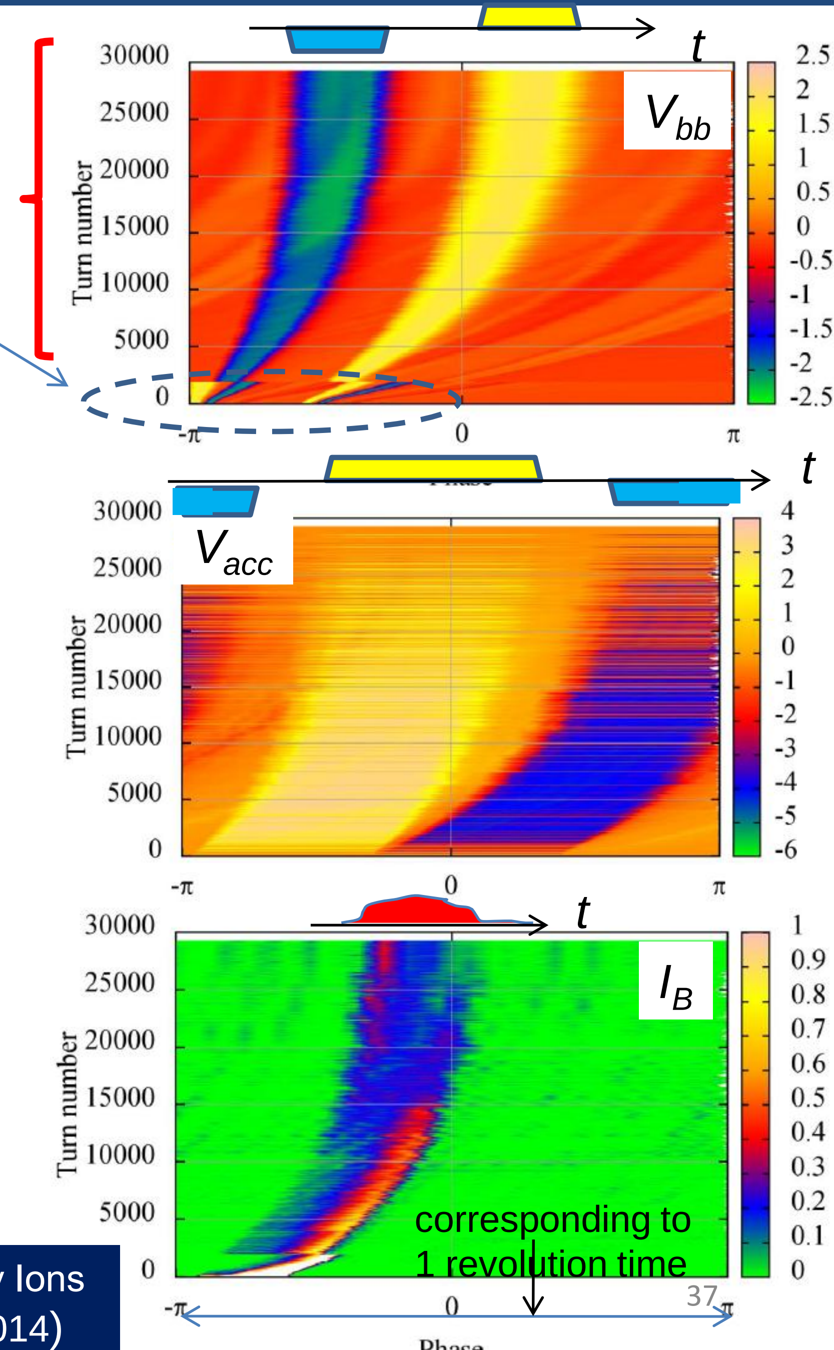
Acceleration of A/Q=4 Ions

1) Early stage of acceleration

2) Late stage of acceleration



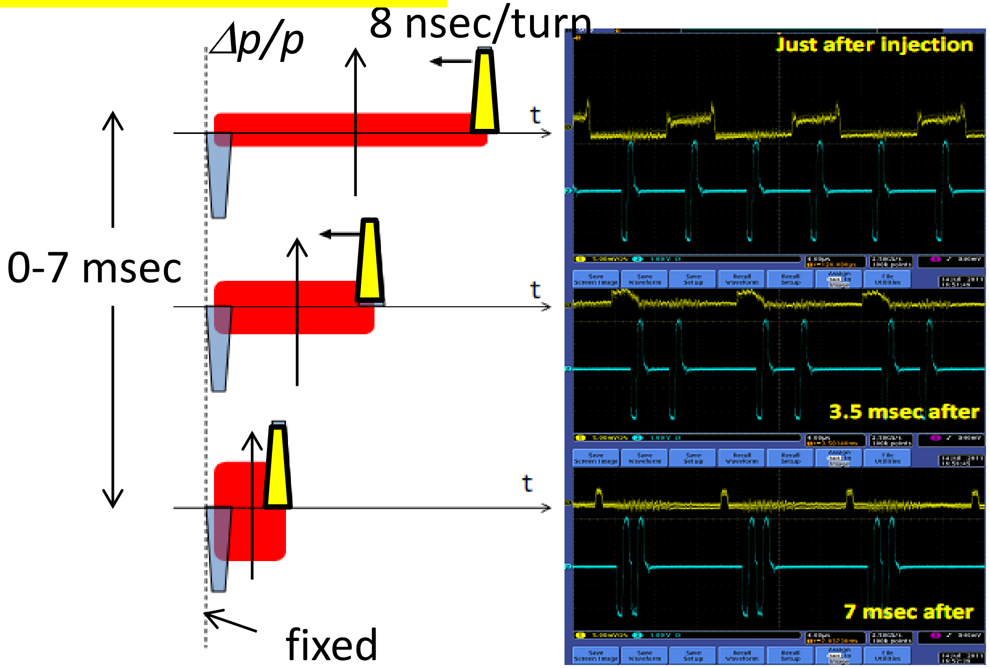


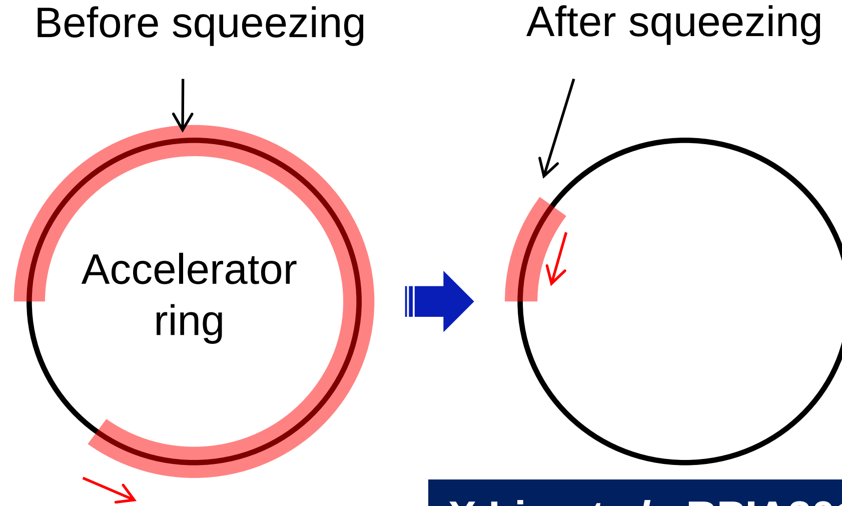


K.Takayama, T.Yoshimoto *et al*., "Induction Acceleration of Heavy Ions in the KEK Digital Accelerator", *Phys. Rev. ST-AB* 17, 010101 (2014)

Flexible Beam Handling in Digital Accelerator

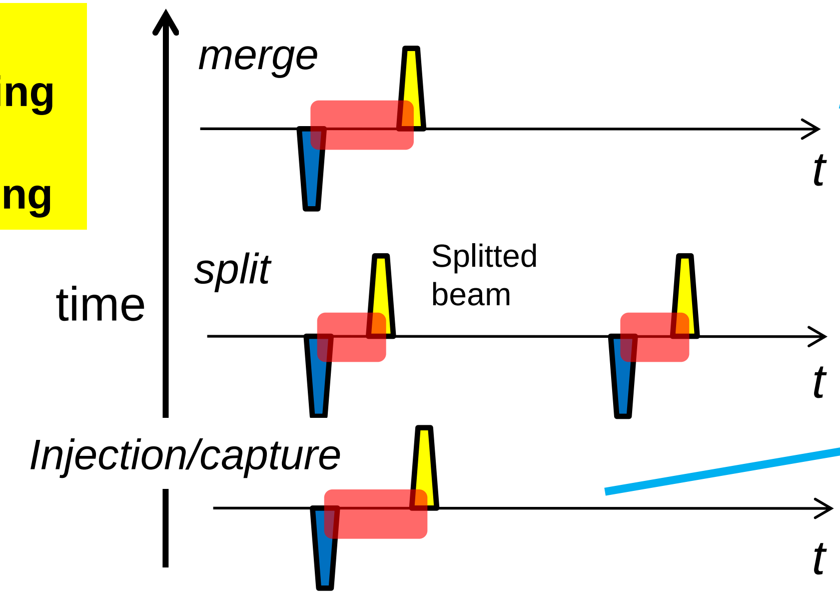
(1) Bunch squeezing



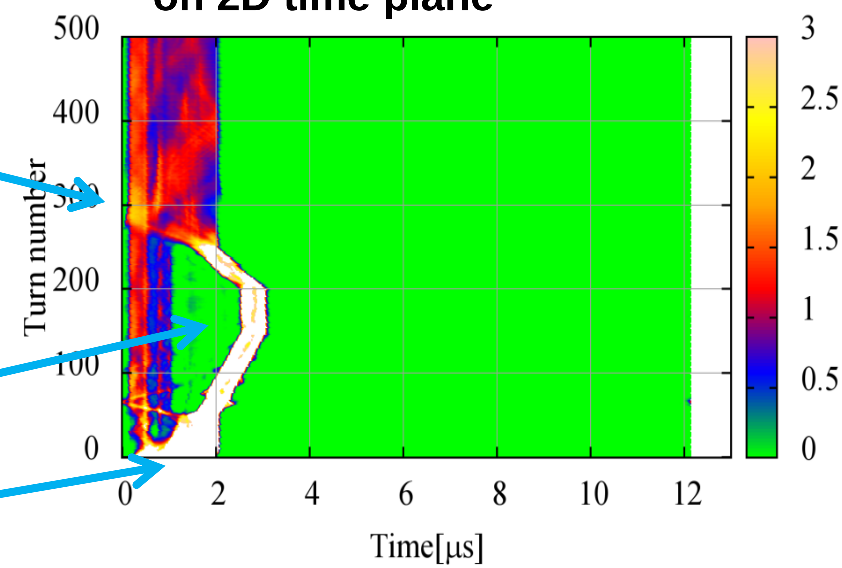


X.Liu *et al.*, RPIA2011

(2) Splitting and merging



Projection of bunch signals on 2D time plane



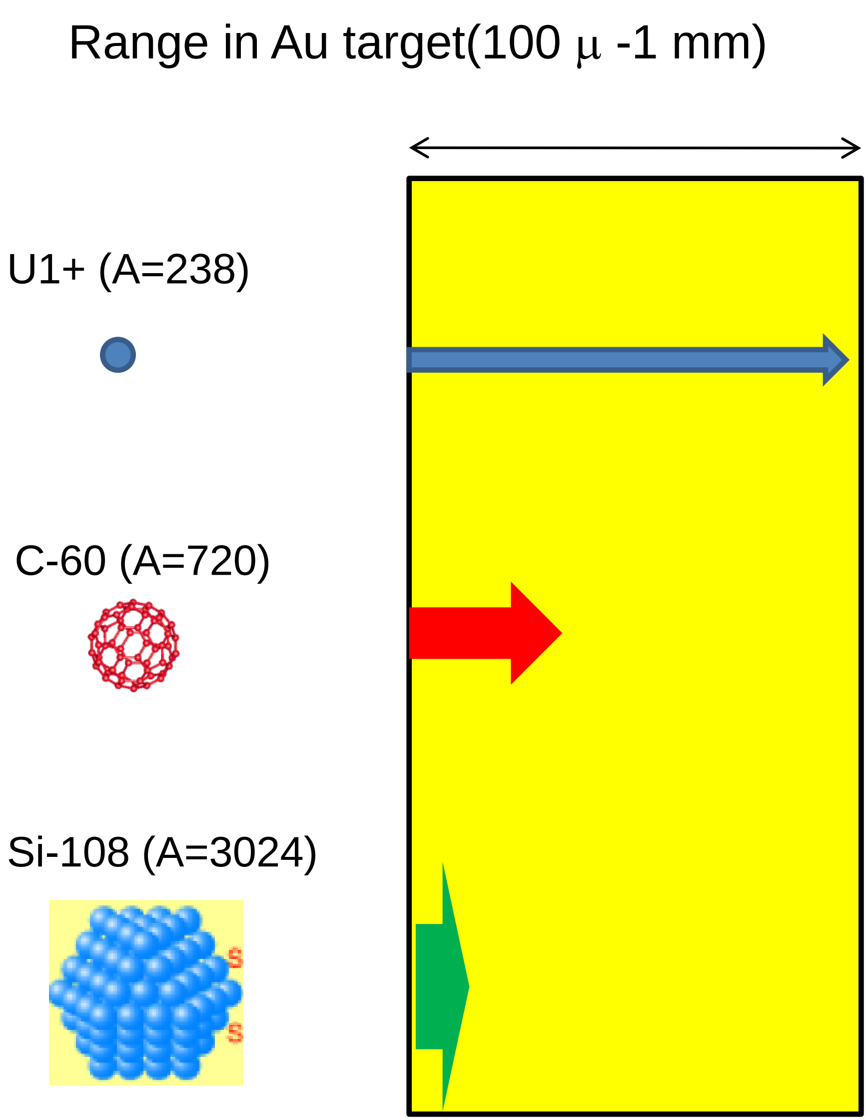
T.Yoshimoto *et al.*, IPAC2014

Giant Cluster Ions as the 4th Generation of High Energy Projectile Particle

- **Extremely large stopping power**
  (Nonlinear effects or Cluster effects)

Entire beam energy is deposited in localized physical space in target material.

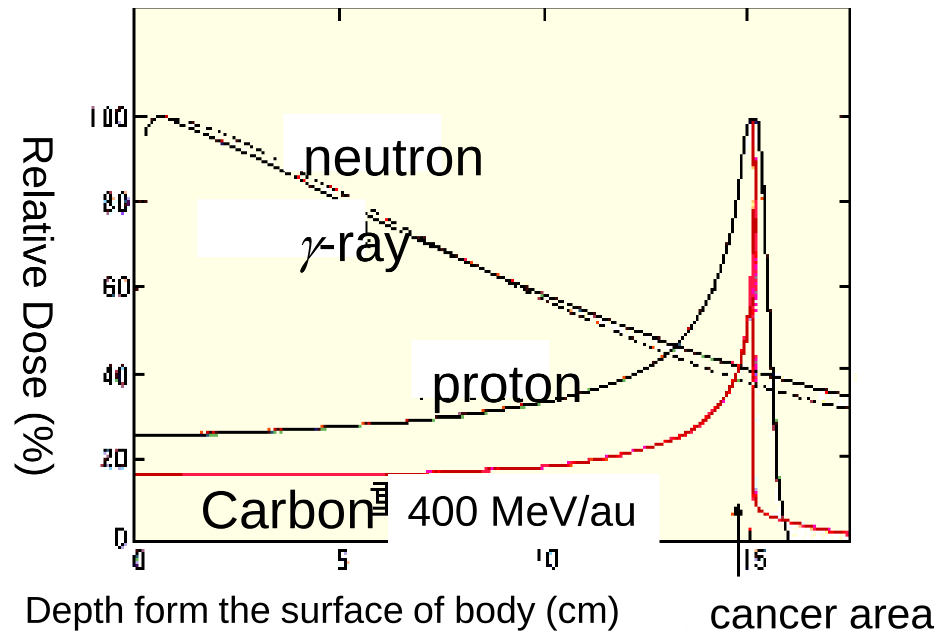
inducing novel states of matter leading to novel materials



with covalent bond structure
cohesive energy ~ 4.15 -4.21 eV

Extremely high energy density in a target

Dose distribution of various quantum beams



A 300 MeV/u Ar beam is penetrating into a Kr-crystal [

Comparison between Induction Synchrotron and its Brothers

Integrated acceleration voltage in a circular ring, which is a parameter being compared with the **acceleration voltage of a single-end electrostatic accelerator**:

$$V[\text{volt}] = \left(\frac{A}{Q}\right)\cdot\frac{mc^2}{e}\cdot\left(\sqrt{1+\left[\left(\frac{Q}{A}\right)\cdot\left(\frac{e}{mc^2}\right)\cdot c\cdot \boxed{B\rho}\right]^2}-1\right)$$

In order to increase ***V***, it is a unique solution to increase ***Magnetic Rigidity***.

A: mass number of cluster ion, *Q*: charge-state
B: flux density of guiding magnet, *ρ*: bending radius

Accelerator	*B*	*ρ*	*Merit/Demerit*
Induction synchrotron	Increasing is in principle possible, introducing S.C. magnet of 8.5 Tesla	fixed	•Low injection fields of S.C. mag. are not stable. •Large aperture required at injection stage does not seem to allow the extremely high field S.C. magnet.
Induction cyclotron (*)	fixed (~ 1.5 Tesla)	Its increasing is inherent property	•Acceleration method there is completely same as that in the induction synchrotron. •**Large size induction core** with race-track shape is required. Its assembling is not easy and it's expensive.
Induction microtron	fixed(~ 1.5 Tesla)	Its increasing is inherent property	•Induction acceleration cell employing a toroidal-shape core is completely same as that for induction synchrotron. •Acceleration method there is completely same as that in the induction synchrotron.

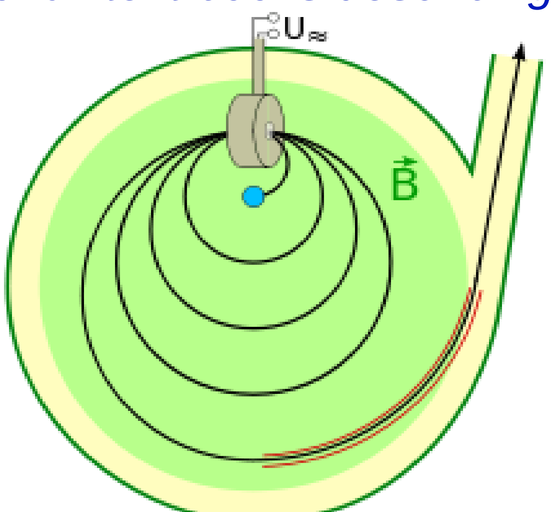
* K.Takayama, T. Adachi, H. Tsutsui, W. Jiang, and Y.Oguri, "Induction Sector Cyclotron for Cluster Ions", *Proceedings of Cyclotron2010*, 331-333 (2011).

Brief History of Microtron

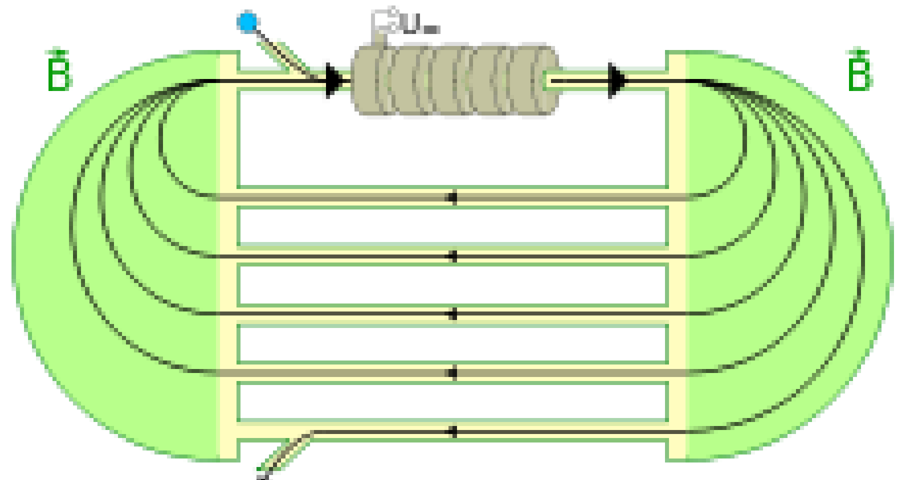
1944 Proposal of Electron Cyclotron by V.I.Veksler (former USSR)
1946-47 Proposals of Electron Microtron
by J. Itoh and D. Kobayashi, J.S.Shwinger, L.I.Shiff

Hereafter The early microtron was constructed in Canada.
1958 Reviewing paper by A. Roberts *Annals of Physics* **4**, 115-165 (1958).
1960-70 Various microtrons had been constructed and dedicated to Nuclear Physics in world wide.
1990- Industries provide a small size microtron for synchrotron radiation sources and constructed as an injector to it.

Two full text books describing electron microtrons are available now.



Classical Microtron
(Typical example : that of RRCAT)

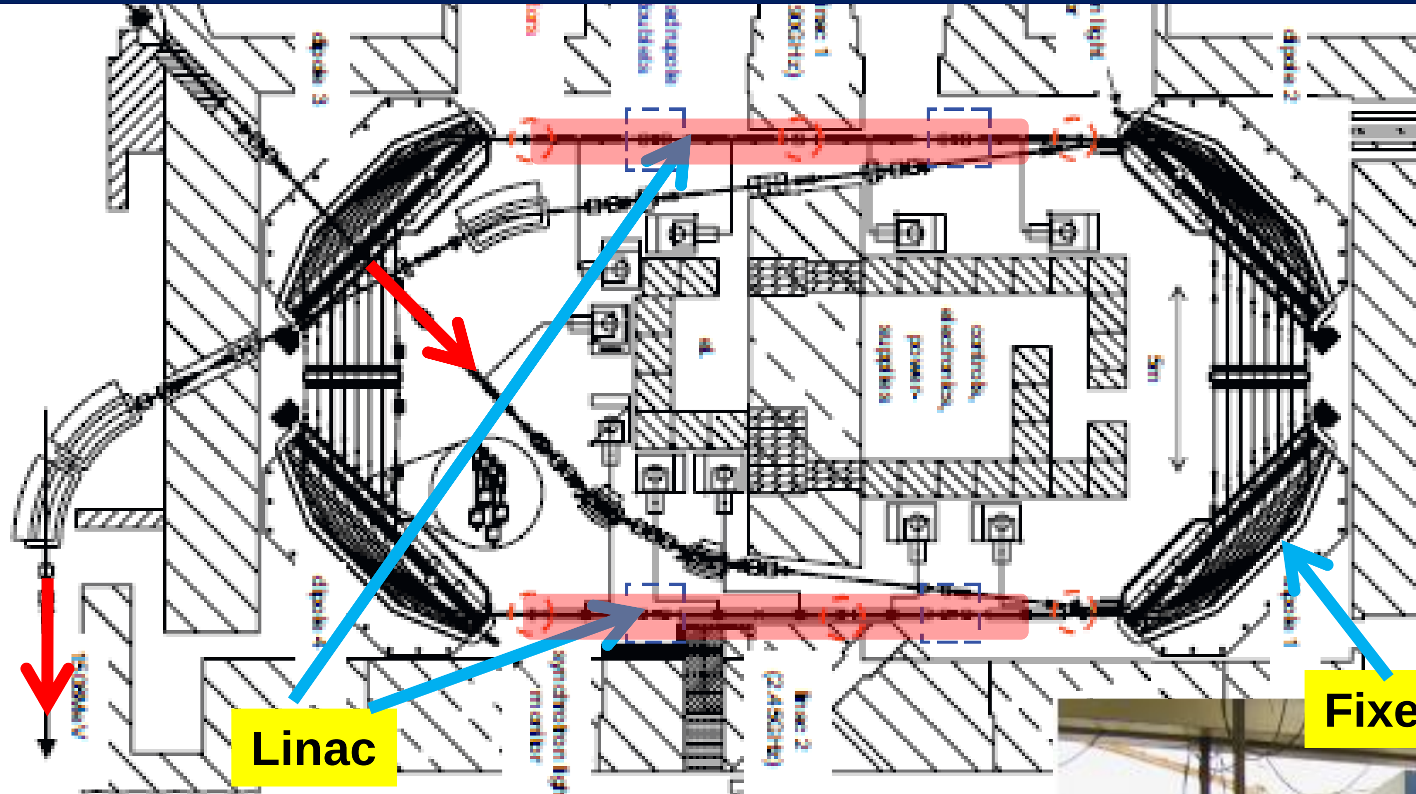


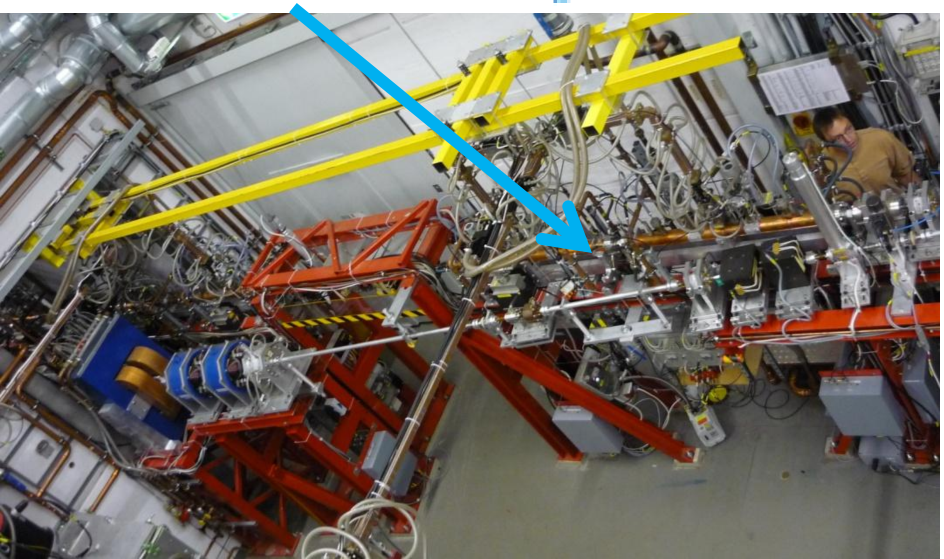
Race track-shape Microtron

from Wikipedia

Existing biggest one: 1.6 GeV e- Microtron of Mainz University

Injection energy: 0.8 GeV
Extraction energy :1.6 GeV
Revolution: ~ 30





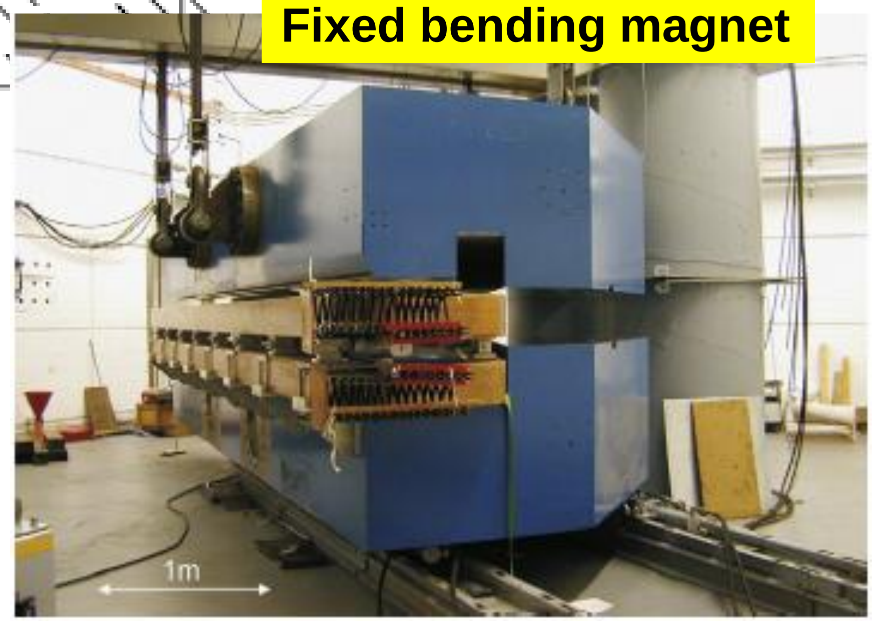
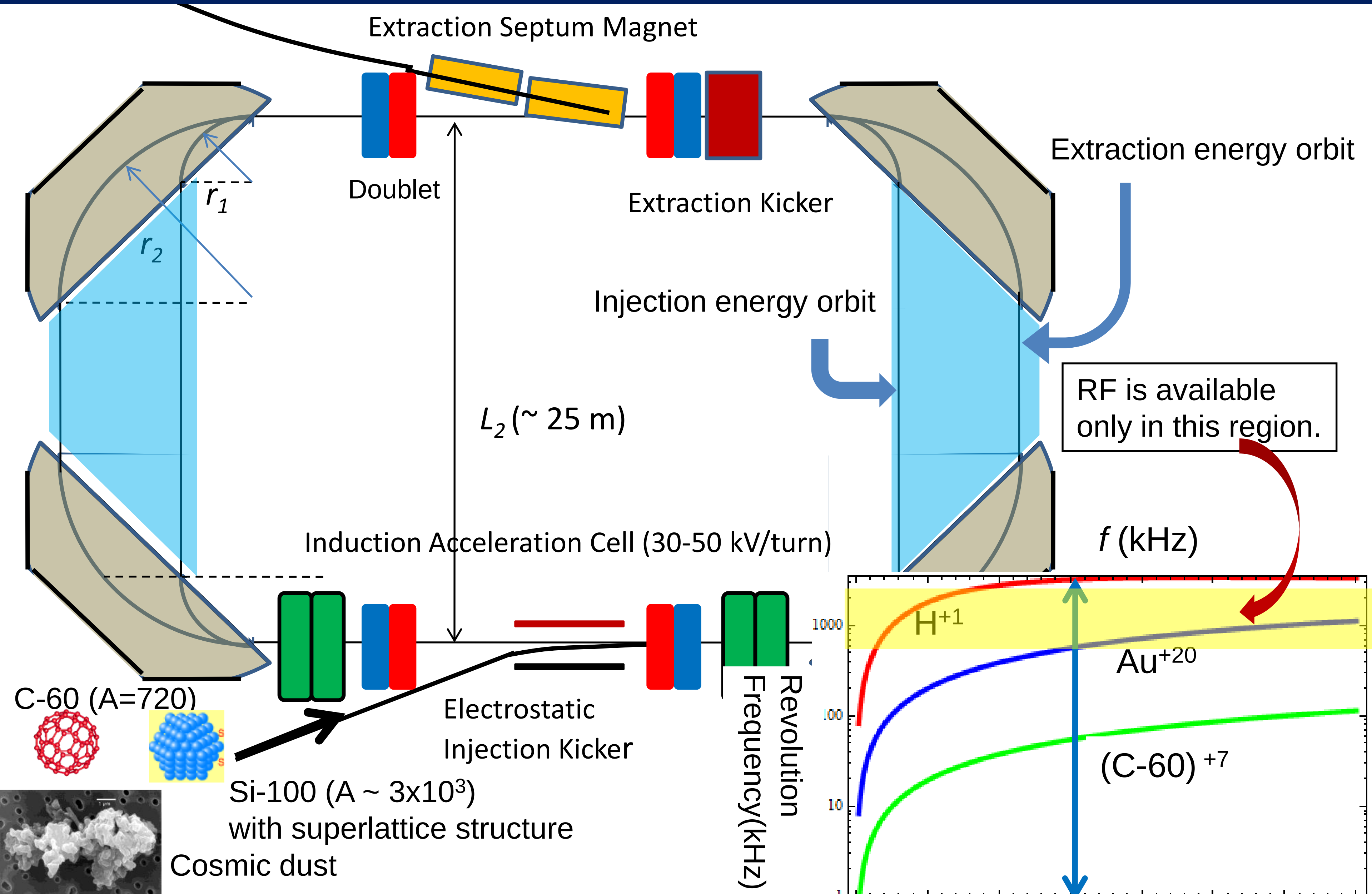


Fig. 12. HDSM-dipole 4 during assembly.

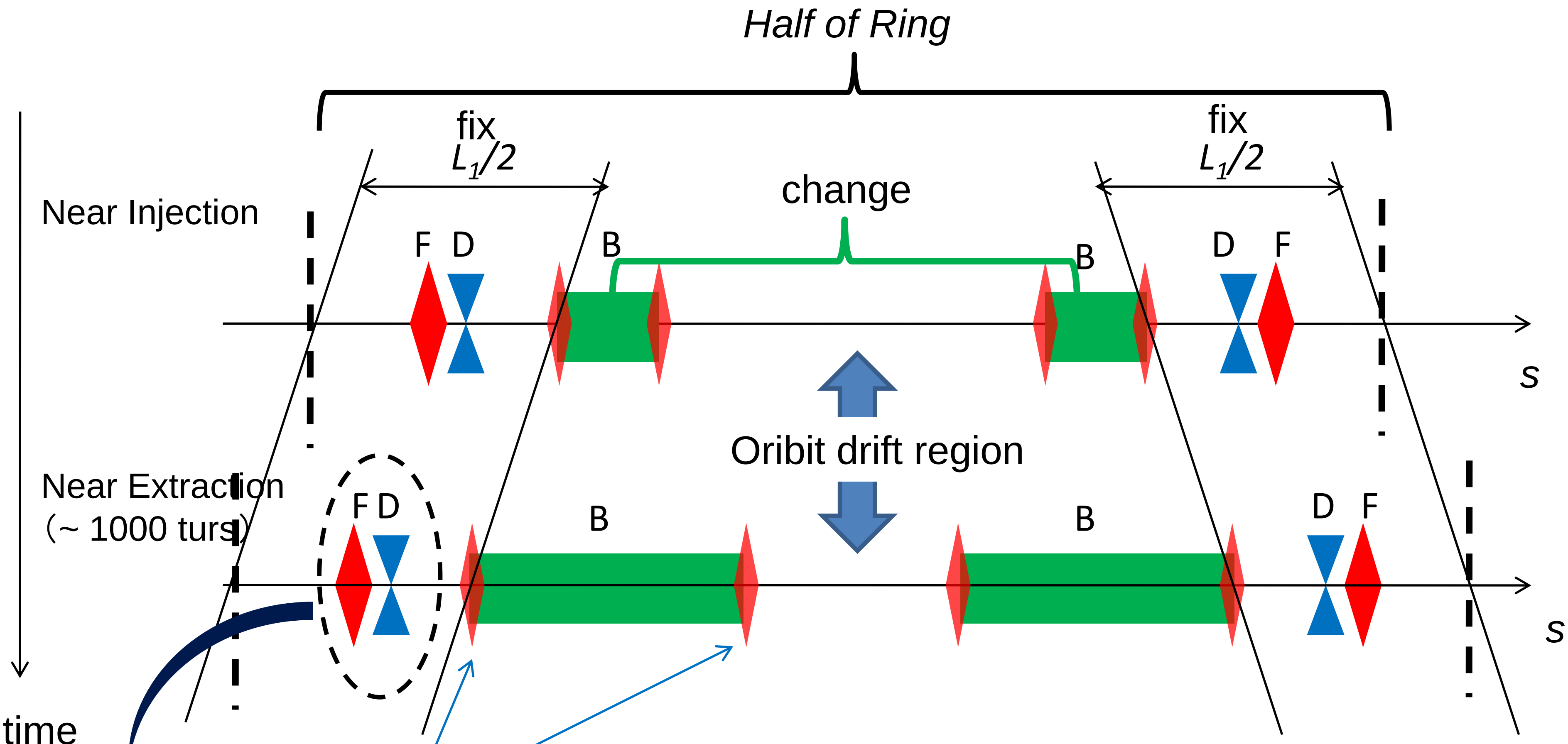
Induction Microtron for Cluster ions and Super heavy micro particles



K.Takayama *et al*., "Induction Microtron for Cluster Ions" published in *Phys. Rev. ST-AB*

How can we guarantee the orbit stability from injection to extraction?

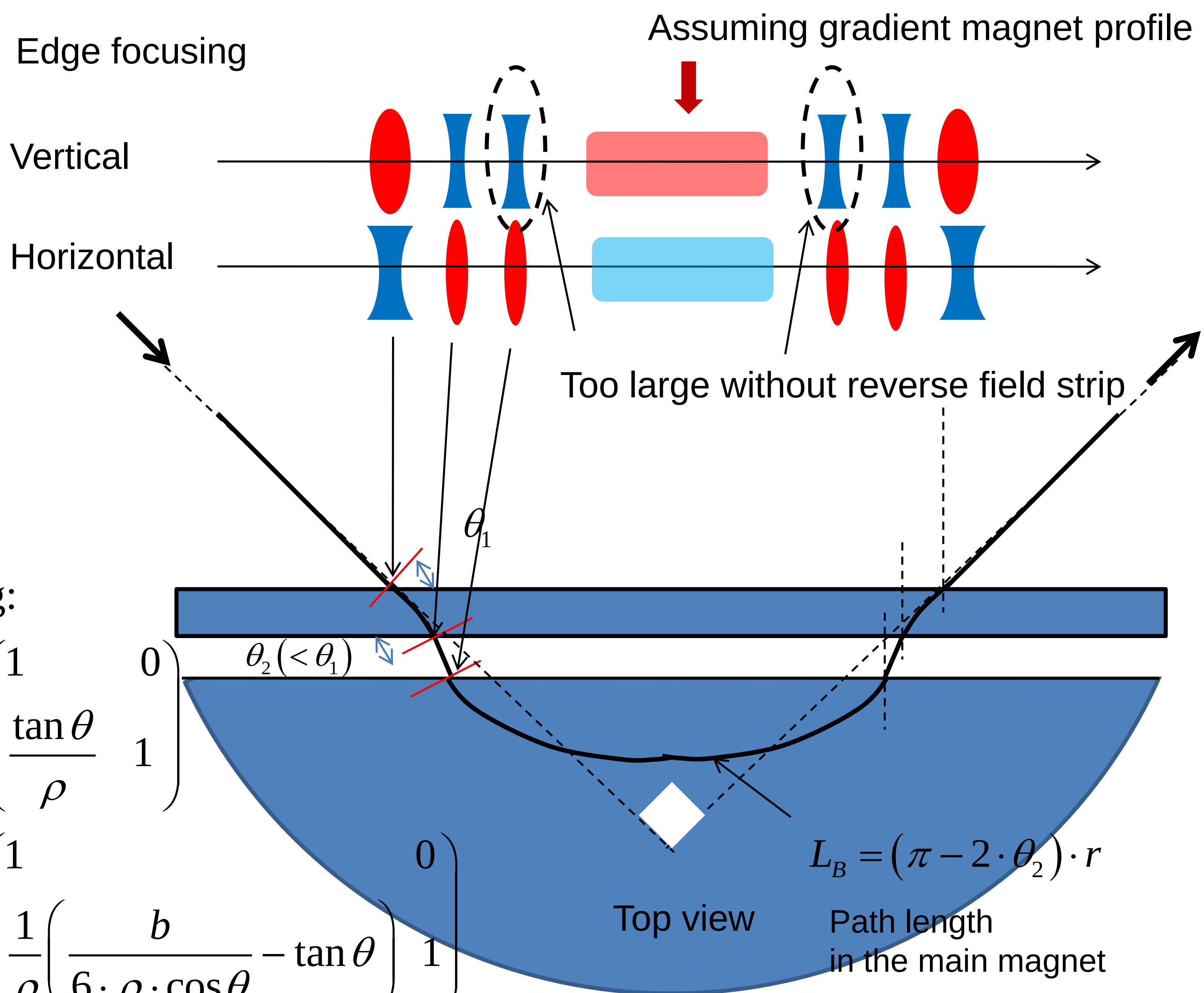
Induction Microtron＝Induction Synchrotron with adiabatically varying orbit length



Edge focusing at both sides of the bending magnet is significant.

It is impossible to keep the stability only by Doublet system

Introducing of Inversed Fields Strip



Edge Focusing:

x-direction: $\begin{pmatrix} 1 & 0 \\ \dfrac{\tan\theta}{\rho} & 1 \end{pmatrix}$

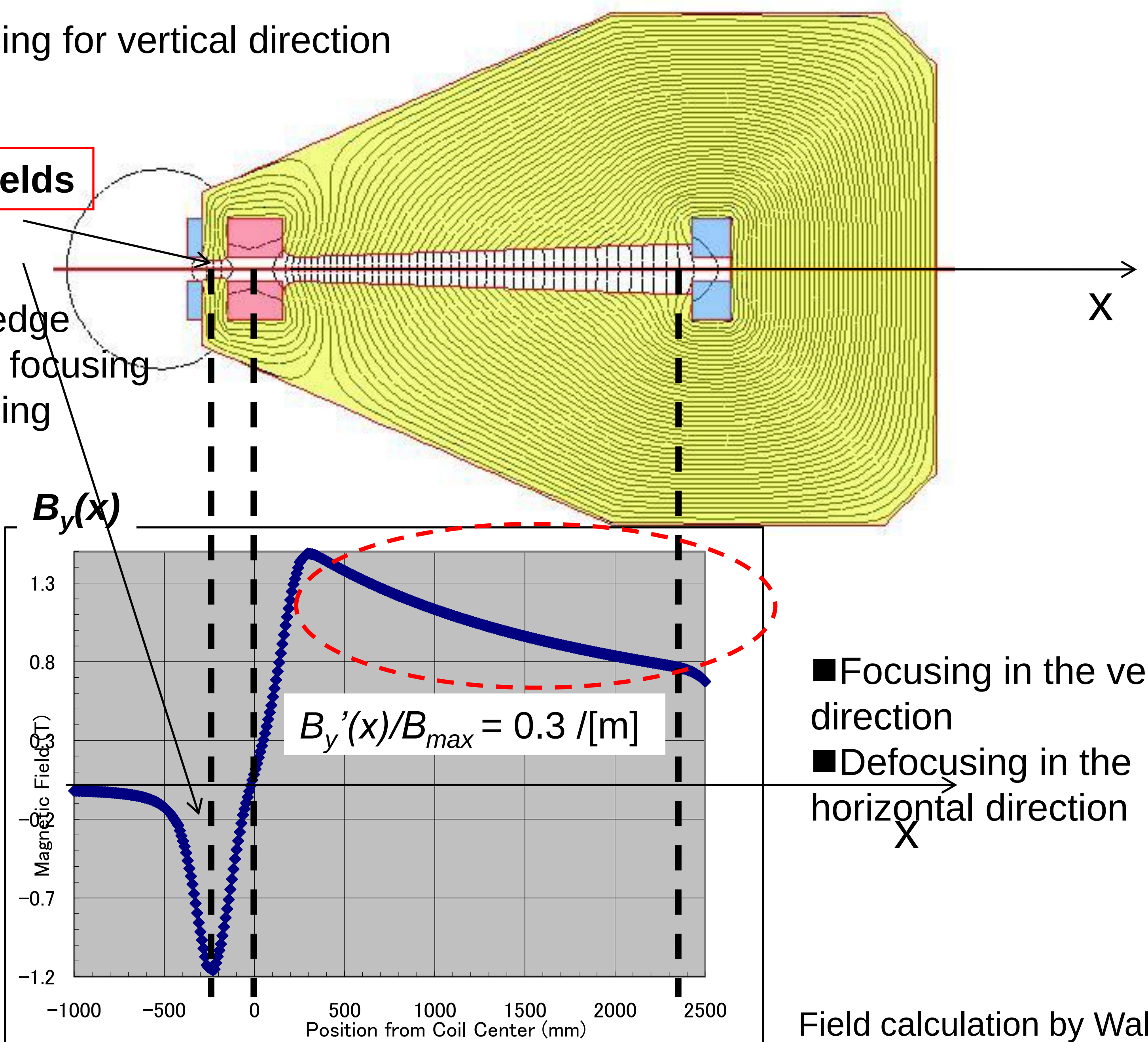
y-direction: $\begin{pmatrix} 1 & 0 \\ \dfrac{1}{\rho}\left(\dfrac{b}{6 \cdot \rho \cdot \cos\theta} - \tan\theta\right) & 1 \end{pmatrix}$

Introducing **Field Gradient** in the Bending Magnet

Defocusing for vertical direction

Reversed fields

at the front edge
Mitigation of focusing and defocusing



■Focusing in the vertical direction
■Defocusing in the horizontal direction

Field calculation by Wake (KEK)

Orbit in Bending Magnet with Uniform Gradient

Orbit in the bending magnet: $Y = Y(X)$

$$\cos\phi == \frac{dY/dt}{v_s}$$

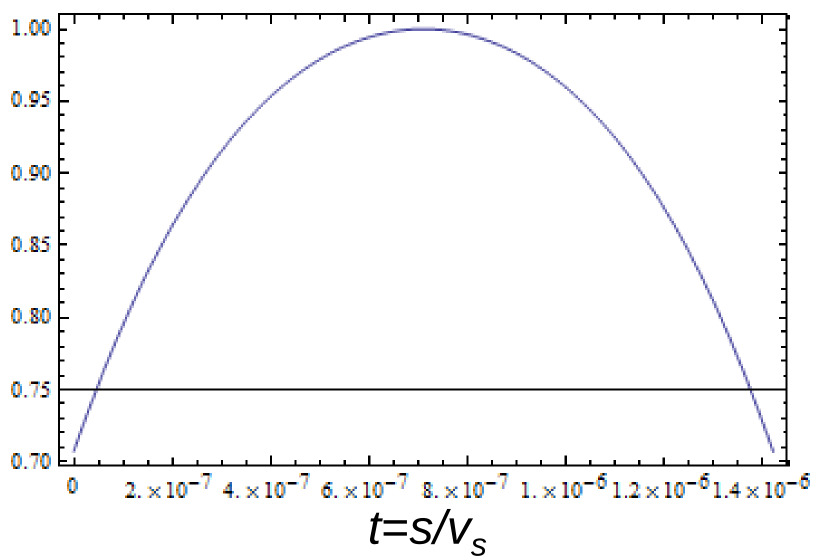
$$\frac{\partial B_y(s)}{\partial x} = \frac{\partial B_y(X)}{\partial X} \cdot \cos\phi$$

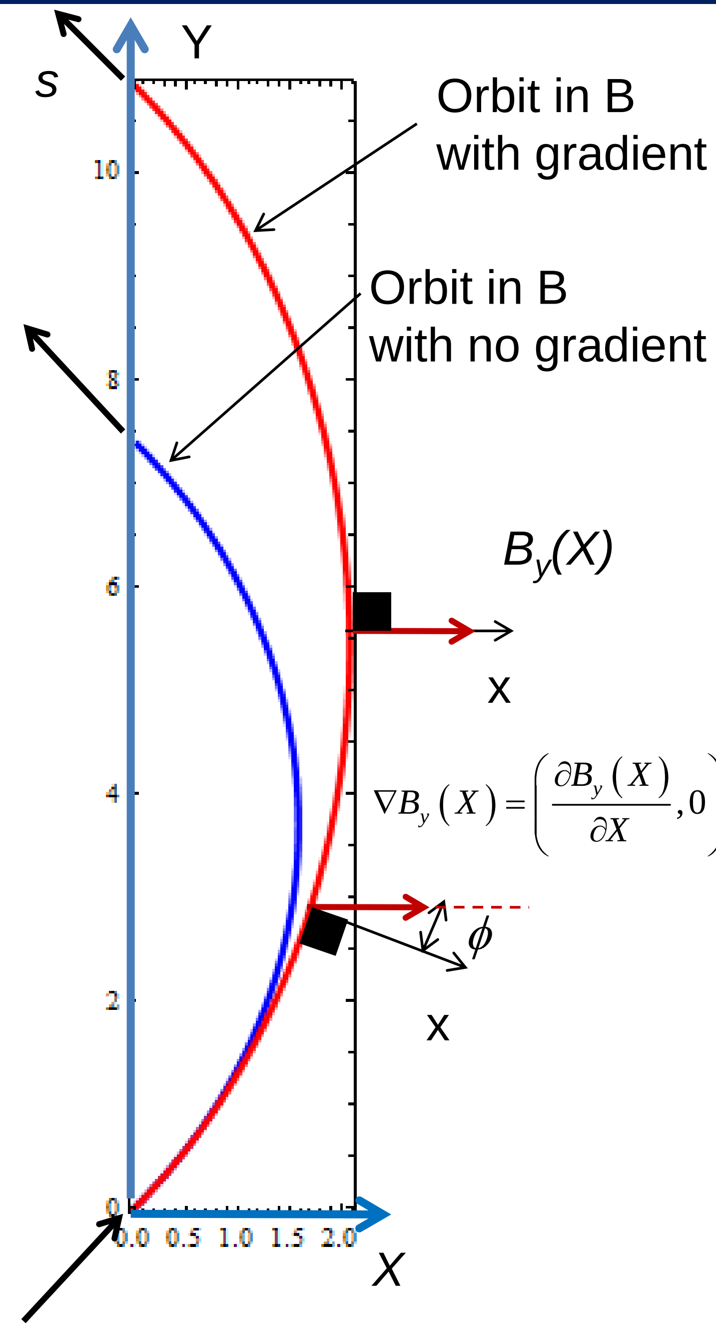
$$s = v_s \cdot t$$

k-value along the orbit: $K(s) = \frac{1}{B\rho} \cdot \frac{\partial B_y(s)}{\partial x} = \frac{\partial B_y(X)}{\partial X} \cdot \frac{\cos\phi}{B\rho}$

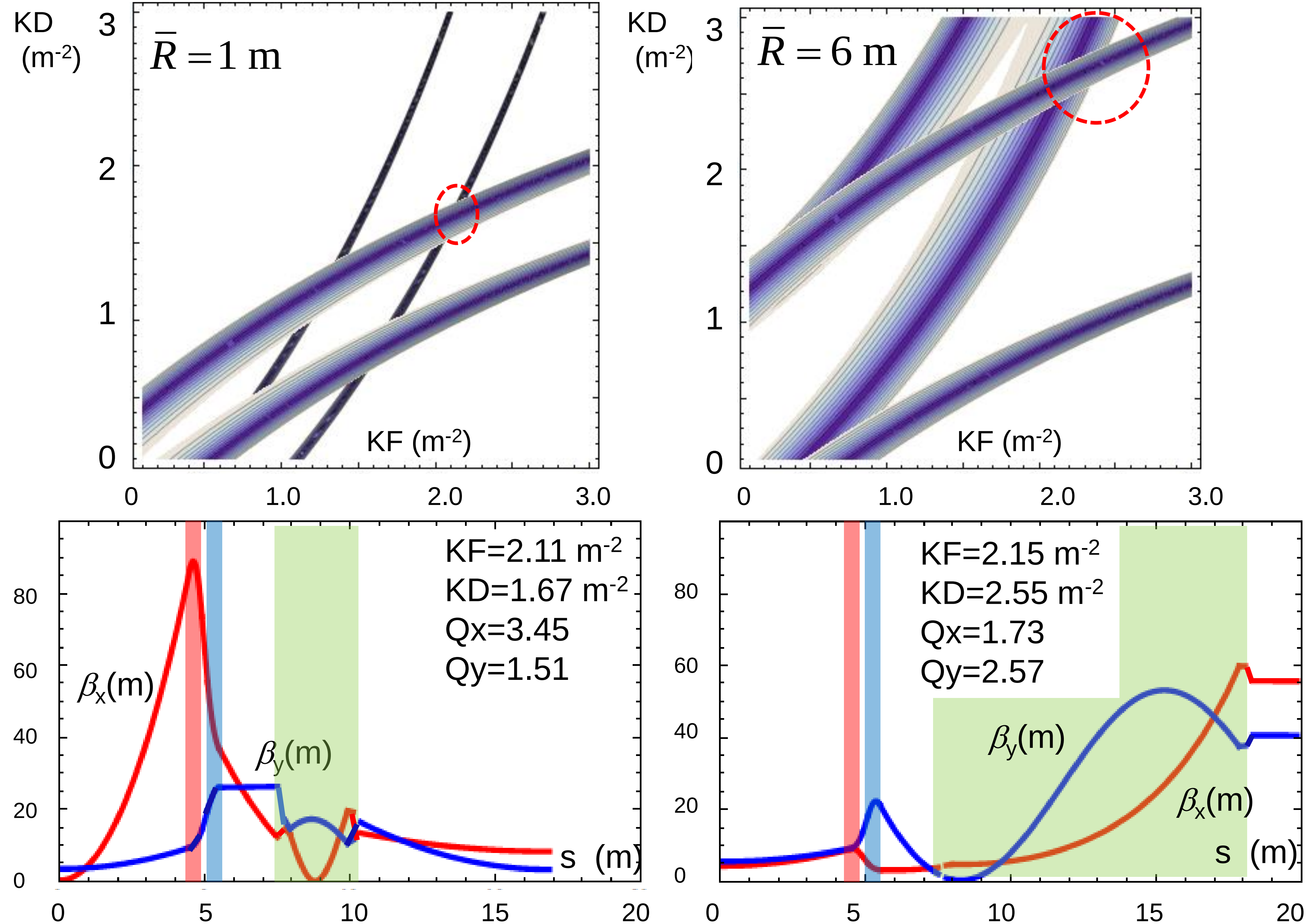
$\cos\phi$ is a reduction factor of k-value.

$\cos\phi$

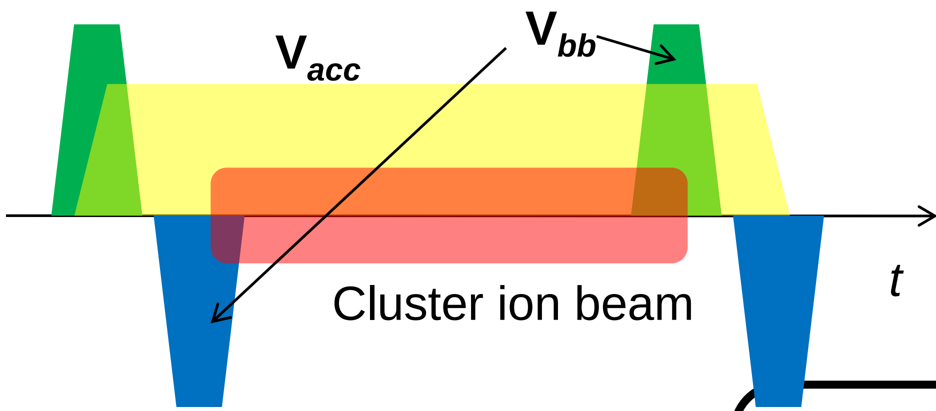




Typical Lattice Functions of 1 Quadrant

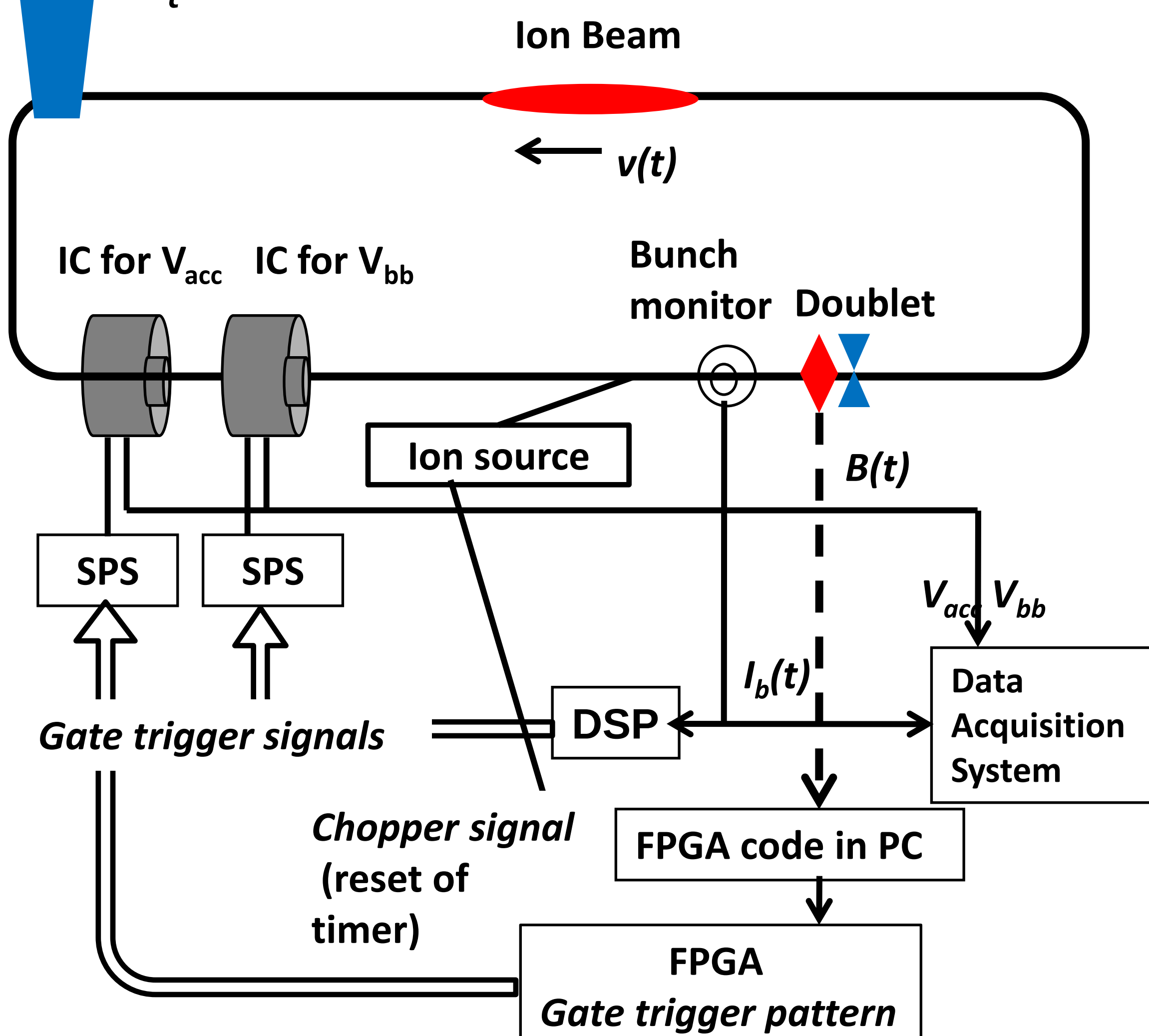


Scenario for Induction Acceleration and Confinement and their Control Procedure



Acceleration and confinement

Flow-chart for control



Summary

- Conventional Circular Hadron Accelerators have achieved a level of state of art.
- Their scale-up is relatively easy.
- New trend is going to begin, adding further flexibility to the existing beam acceleration and handling technology

Induction Circular Accelerators with:

- Time-varying guide-fields → *Induction Synchrotron*
- Fixed guide-fields → *Induction Microtron*

Induction Micotron may be indispensable to accelerate stable giant cluster ions such as C-60 or Si-100 to high energy. Giant cluster ions may be the 4^{th} generation of accelerating particle following e-, proton, and heavy ion.