Accelerator Physics research in KEK

KEK, Acc. 2nd div.
J-PARC center, Acc. Cont. Gr.
Noboru Yamamoto

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  - LINAC/PF/PF-AR/SuperKEKB
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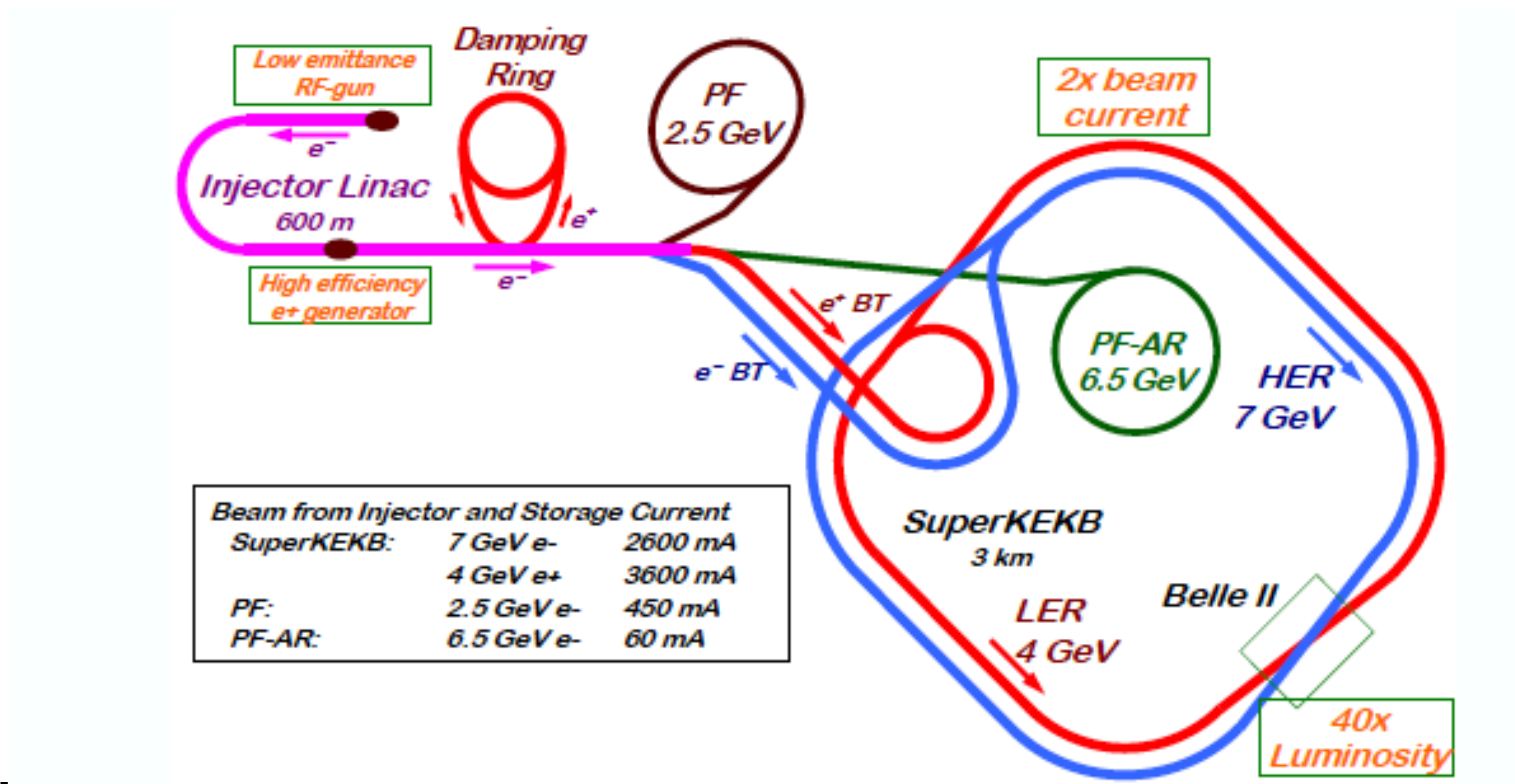
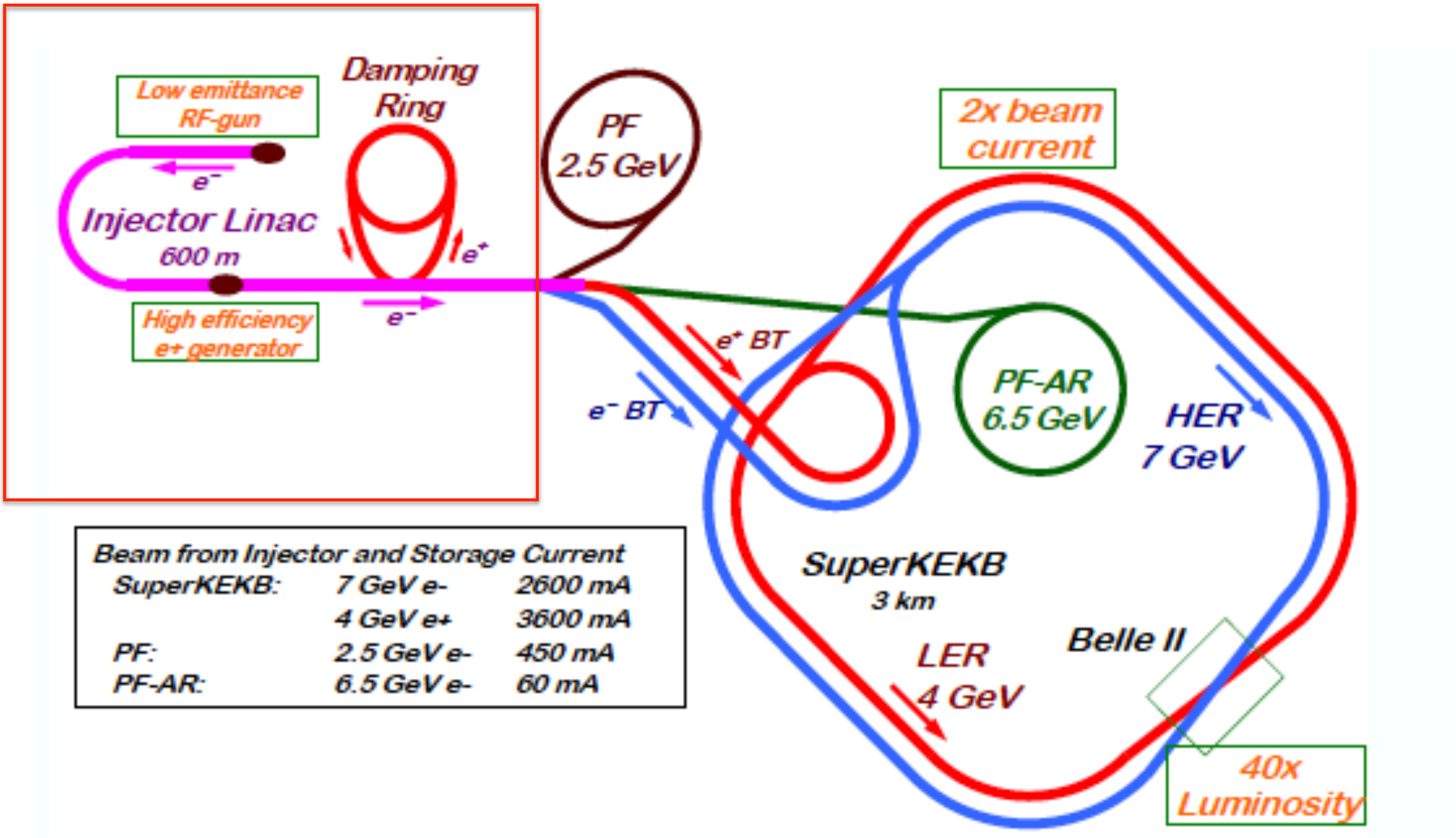
- Introduction to Acc. Phys.

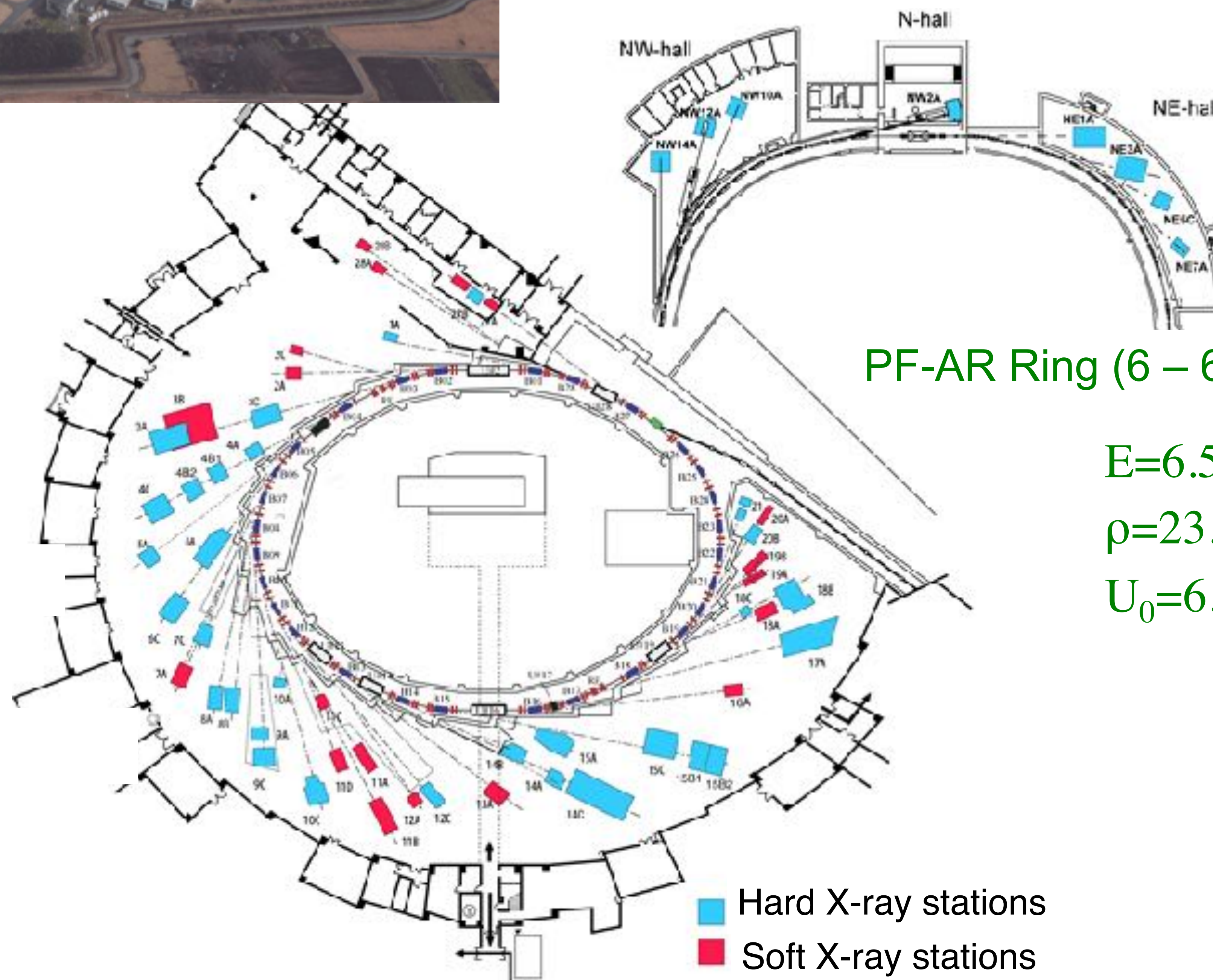


Electron/positron injector linac



K. Furukawa

SR rings in KEK



PF-AR Ring (6 – 6.5 GeV)

E=6.5 GeV

ρ=23.2 m

U_0=6.8 MeV

PF Ring (2.5 – 3GeV)

E=2.5 GeV

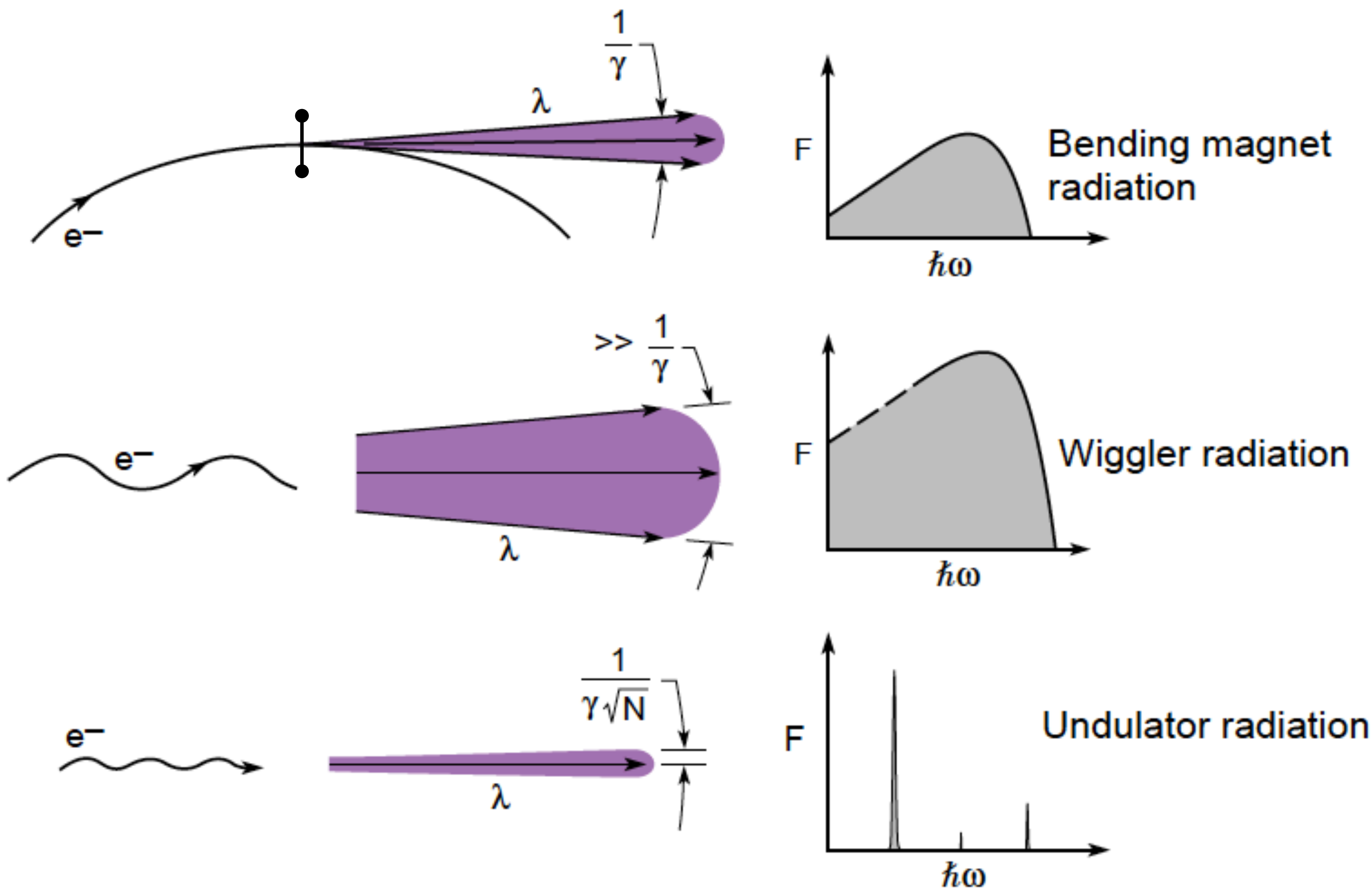
ρ=8.66 m

U_0=0.4 MeV

Hard X-ray stations

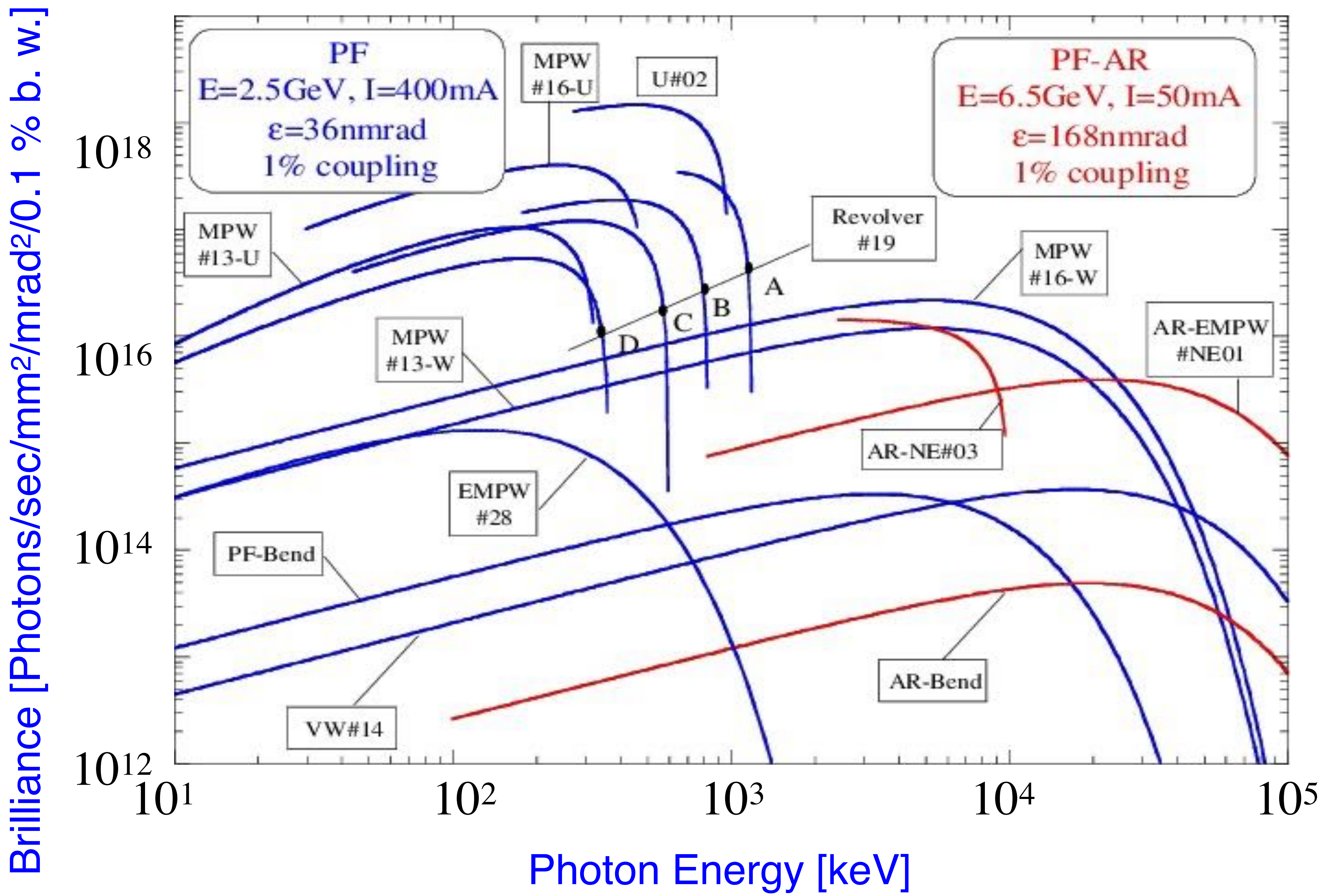
Soft X-ray stations

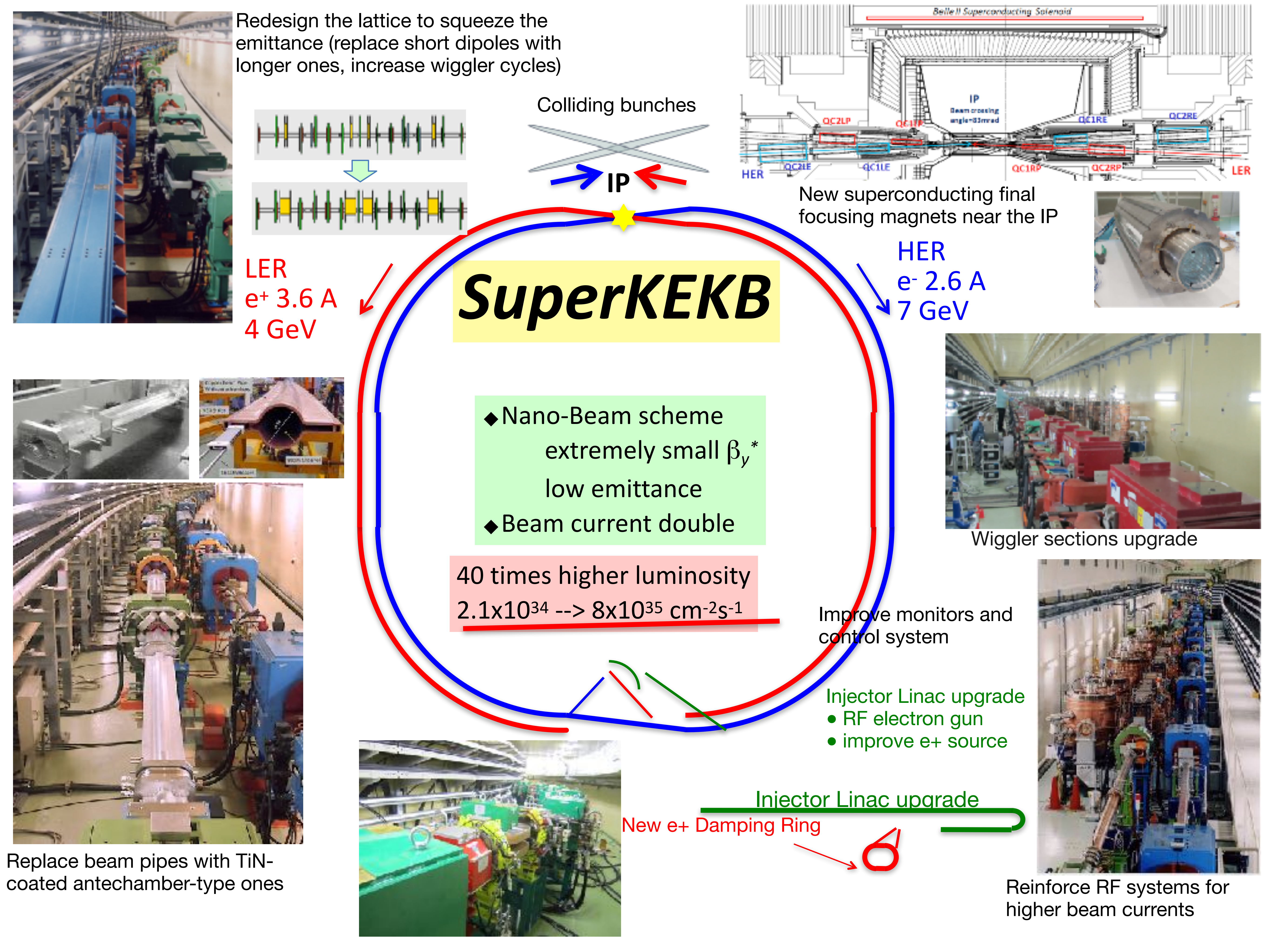
Forms of synchrotron radiation



D. Attwood, "Soft X-ray and Extreme Ultraviolet Radiation: Principles and Applications",Cambridge University Press

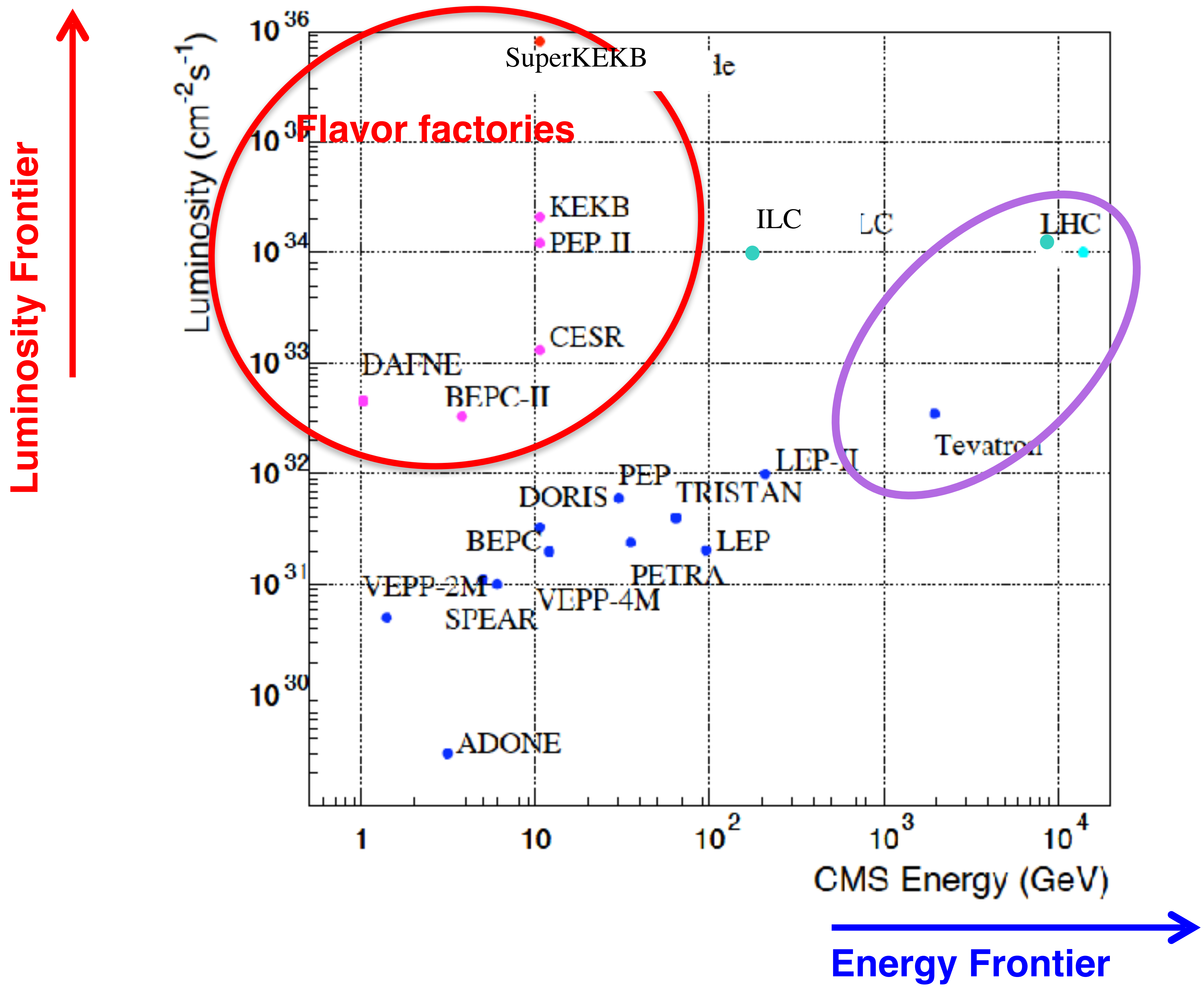
Brilliance of PF and PF-AR





Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)
Colliding bunches
IP
Belle II Superconducting Solenoid
IP
Beam crossing angle=83mrad
QC2LP
QC1LP
QC1RE
QC2RE
HER
QC2LE
QC1LE
QC1RP
QC2RP
LER
New superconducting final focusing magnets near the IP
LER
e+ 3.6 A
4 GeV
HER
e- 2.6 A
7 GeV
SuperKEKB
◆Nano-Beam scheme
extremely small β_y^*
low emittance
◆Beam current double
40 times higher luminosity
2.1×10^{34} --> 8×10^{35} $cm^{-2}s^{-1}$
Wiggler sections upgrade
Improve monitors and control system
Injector Linac upgrade
• RF electron gun
• improve e+ source
Injector Linac upgrade
New e+ Damping Ring
Replace beam pipes with TiN-coated antechamber-type ones
Reinforce RF systems for higher beam currents

CMS Energy and Luminosity



J-PARC

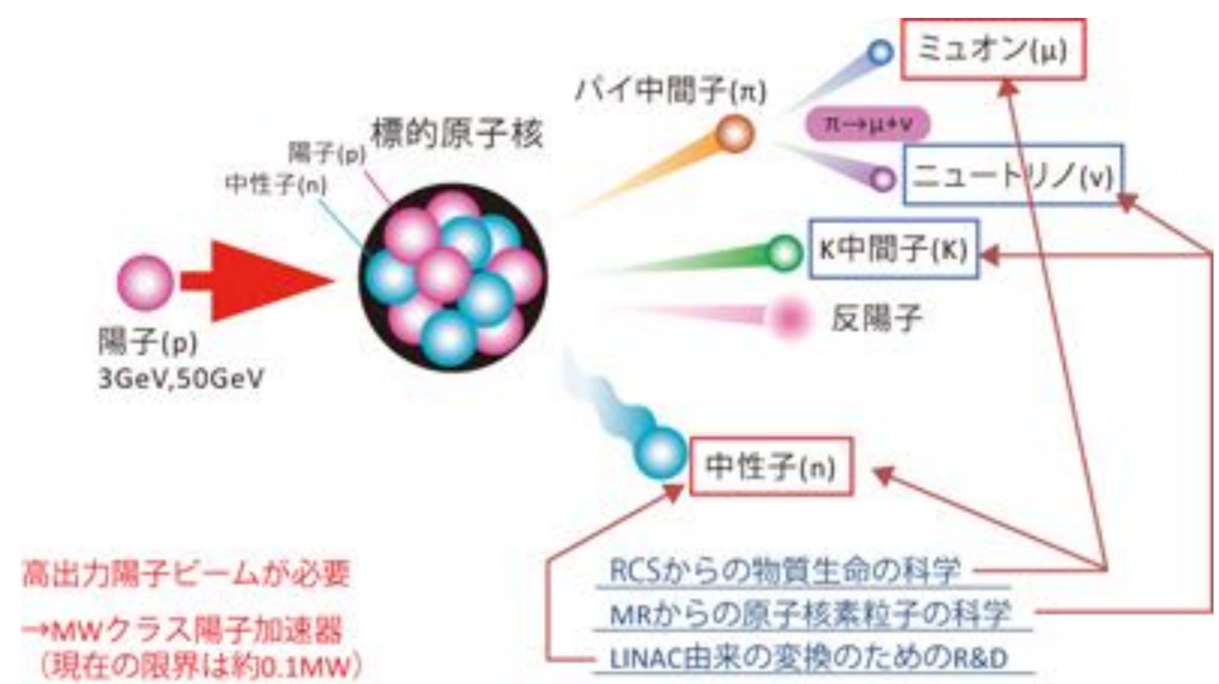
- Joint project between JAEA and KEK.
  Build in Tokai-mura, Ibaraki.

- Three Exp. Facilities:

  - MLF(Material and Life science Facility)：Neutron, Muon

  - NU(Neutrino Exp. Facility)：Neutrino

  - HD(Hadron Exp. Hall): π, K



- Three Accelerators：
  LINAC: Linear Accelerator　(400MeV)
  RCS　: Rapid Cycling Synchrotron (3GeV)
  MR　　: Main Ring　(30GeV)

shorter wave for study of tiny matter

de Broglie Wave

wavelength: $\lambda = \frac{h}{p}$ — h: Planck constant, p: momentum

- higher resolution = shorter wavelength = higher momentum
  → High Energy Accelerators
- Different particles(interaction) show different view of matter.
  → Various type of accelerators and secondary beams.

Brief introduction to Accelerator Physics

- Beam Transport
  - Strong Focusing : Betatron oscillation
- Acceleration
  - Phase stability: Synchrotron oscillation
- Beam Instability
  - Betatron Resonance
  - Space Charge Effect

Charged particle motion

- Lorentz Force:

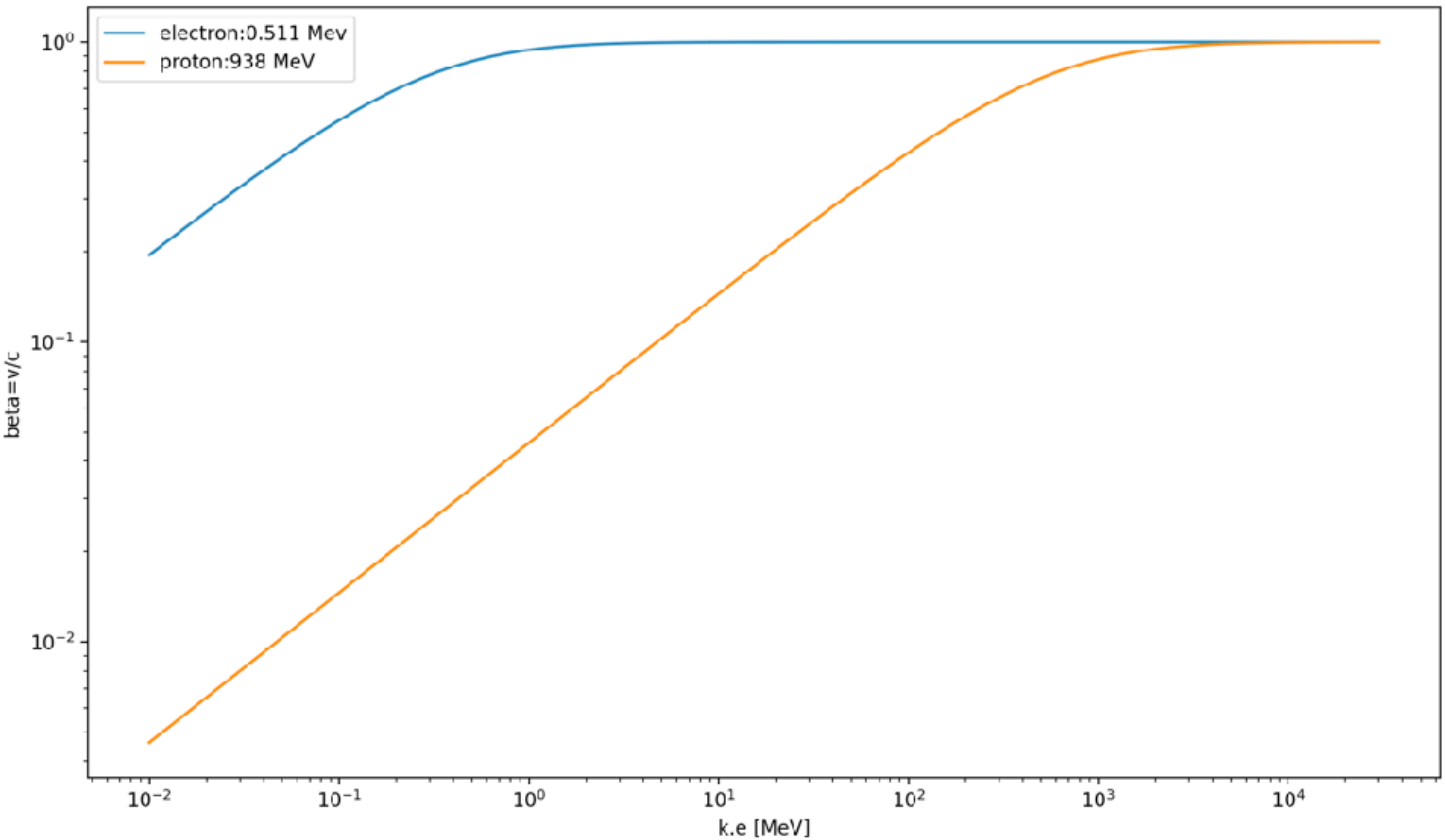
$$\frac{d\overrightarrow{p}}{dt} = \overrightarrow{F} = e\overrightarrow{E} + e\overrightarrow{v} \times \overrightarrow{B}$$

- Electric field equivalent to 1T magnetic field
  - at v ~ c,   B= 1T is equivalent to E ~ c B = 300 MV/m
  - if we take E= 20 MV/m, v ~ E/B = 20 MV/m /1T = 2e7 m/sec,
    - i.e. for Low energy particle, v << 2e7 m/sec (β~0.07, γ~ 1.002), Electric field has advantage.
- We need to have Electric field to increase energy.

$$\frac{dE}{dt} = \overrightarrow{v} \cdot \frac{d\overrightarrow{p}}{dt} = e\overrightarrow{v} \cdot \overrightarrow{E} + e\overrightarrow{v} \cdot \left(\overrightarrow{v} \times \overrightarrow{B}\right) = e\overrightarrow{v} \cdot \overrightarrow{E}$$

- In High Energy Accelerators
  - Electric field is used fo acceleration
  - Magnetic field is used for beam orbit control.

Velocity and Kinetic Energy of a particle

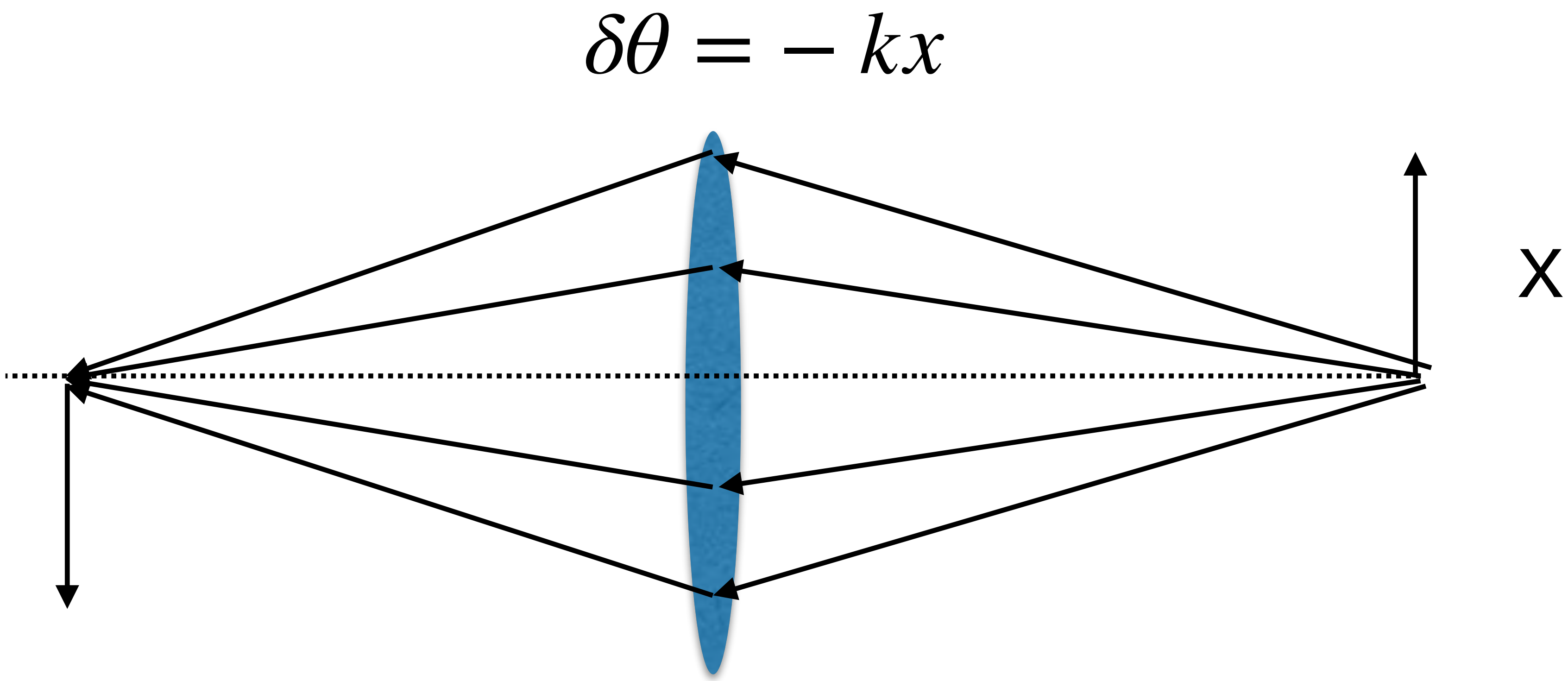


Magnetic field for beam control

- In accelerators, particle travel very long distance.
  - In J-PARC MR: protons circulate rings 480,000 times before extraction. ~768,000 km
- Uniform Field $\overrightarrow{B} = B_0 \overrightarrow{e_y}$
  - → Circular motion
  - → changes direction of motion
  - → Works like a "Prism"
- What about "Lenses" ?

J-PARC MR bending Magnet

What is "Lens"



$$\begin{pmatrix}1 & a\\0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\-1/f & 1\end{pmatrix}\begin{pmatrix}1 & b\\0 & 1\end{pmatrix}$$

$$\begin{pmatrix}-\frac{b}{a} & 0\\-\frac{a+b}{ab} & -\frac{a}{b}\end{pmatrix} \quad \text{with } \frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

Focusing with Magnet

- Focusing Force：Force proportional to the displacement from origin, x.

$$\overrightarrow{B} = kx\overrightarrow{e_y} \rightarrow F_x = -ev_z kx$$

- to satisfy Maxwell's equation, it should be:

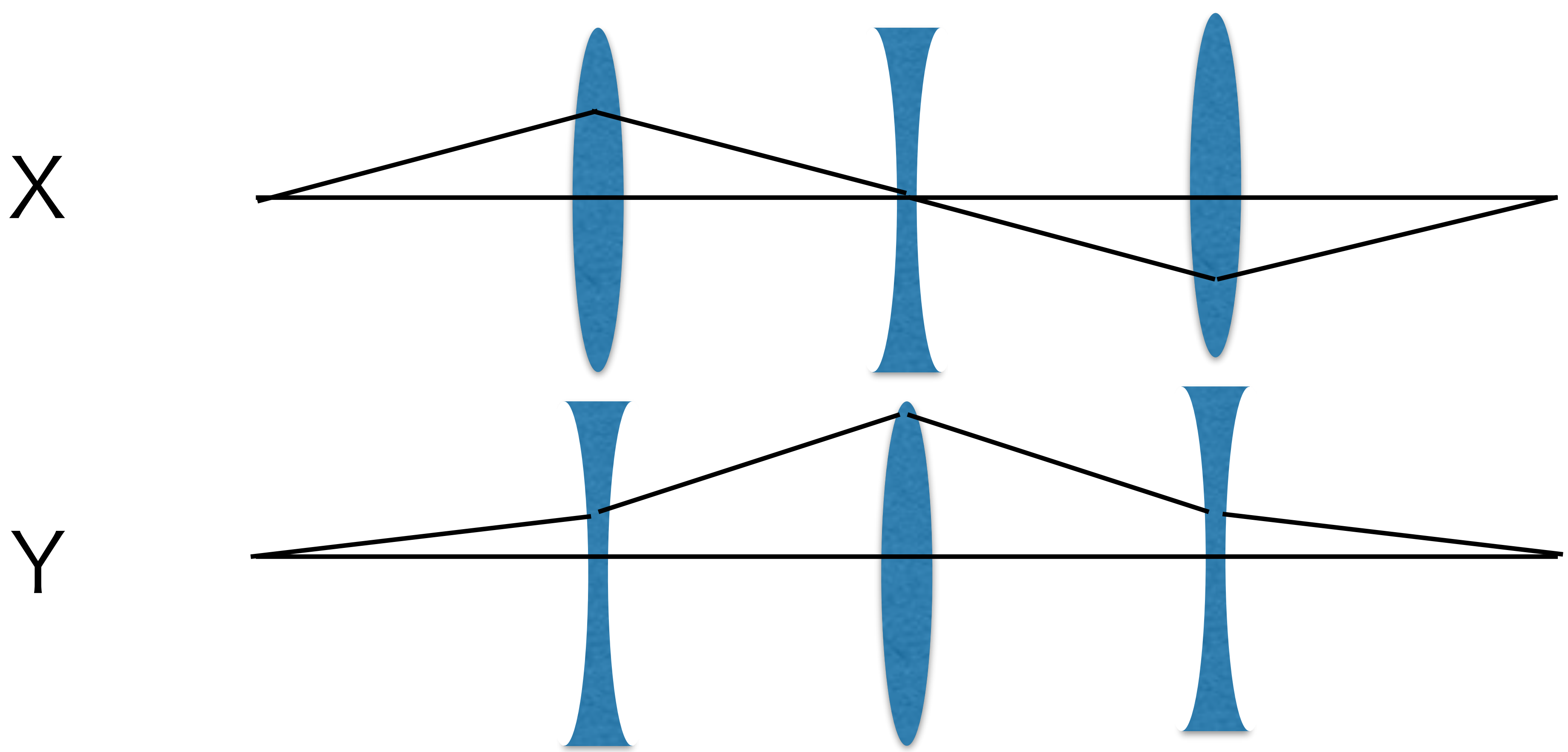
$$\overrightarrow{B} = kx\overrightarrow{e_y} + ky\overrightarrow{e_x}$$

- Force received by a particle moving to z-direction. ->

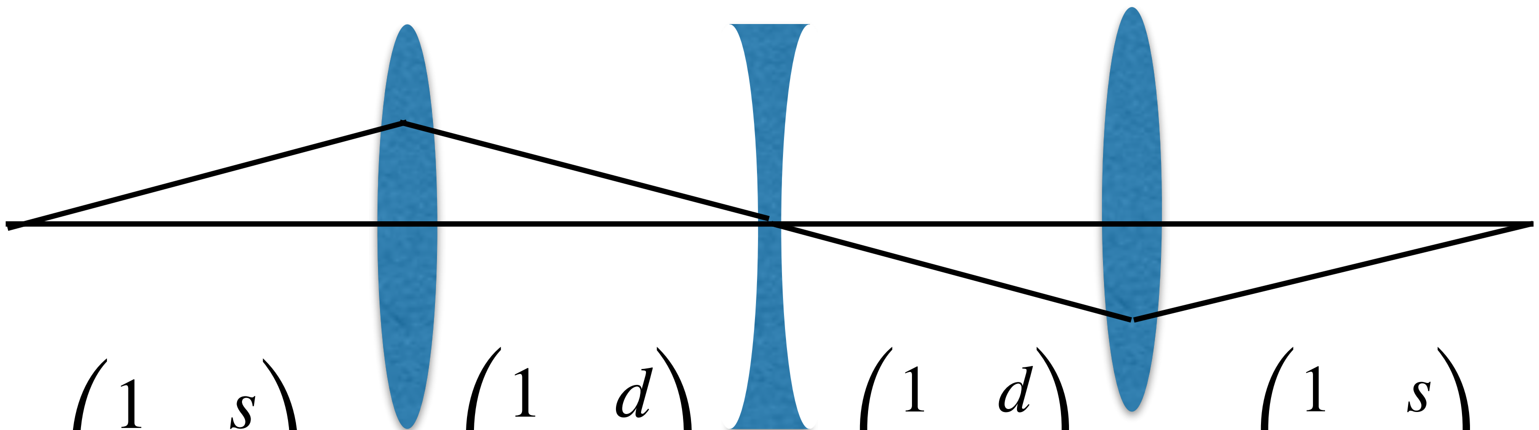
$$\overrightarrow{F} = e\mathrm{v}_0\overrightarrow{e_z} \times \overrightarrow{B} = -ek\mathrm{v}_0 x\overrightarrow{e_x} + ek\mathrm{v}_0 y\overrightarrow{e_y}$$

Principle of Strong Focusing

- Combining two types of (Quadrupole) magnets, the system can have focusing forces for both X and Y directions。



Transfer matrix



$$\begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 \\ -k_2 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ k_1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -k_2 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 \\ \dfrac{2d^2 + 5ds + 4s^2}{d^3 + d^2 s} & 1 \end{pmatrix}$$

$$\begin{pmatrix} -1 & 0 \\ -\dfrac{2d + s}{d^2 + ds} & -1 \end{pmatrix}$$

$$\begin{pmatrix} (dk_1^2 - k_1)k_2 s^2 - 2dk_1 + dk_2 + \left(2dk_1^2 - (2dk_1 - 1)k_2 - 2k_1\right)s + 1 & (d^2k_1^2 - 2dk_1 + 1)k_2 s^2 - 2d^2k_1 + d^2k_2 + 2\left(d^2k_1^2 - 2dk_1 - (d^2k_1 - d)k_2 + 1\right)s + 2d \\ k_1^2 k_2 s^2 + 2(k_1^2 - k_1 k_2)s - 2k_1 + k_2 & (dk_1^2 - k_1)k_2 s^2 - 2dk_1 + dk_2 + \left(2dk_1^2 - (2dk_1 - 1)k_2 - 2k_1\right)s + 1 \end{pmatrix}$$

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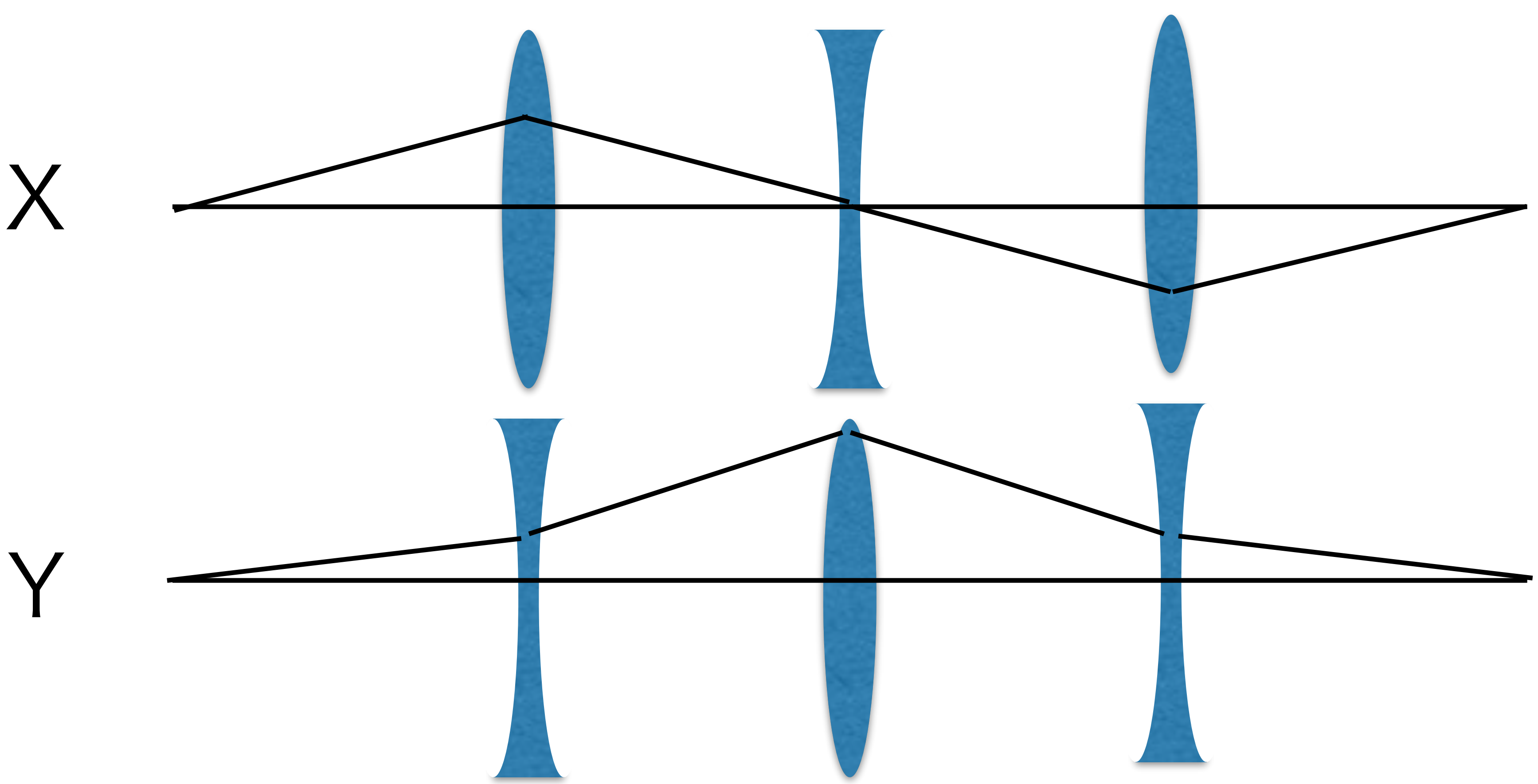

$$\begin{pmatrix} 1 & 0 \\ \frac{2d^2+5ds+4s^2}{d^3+d^2s} & 1 \end{pmatrix}$$

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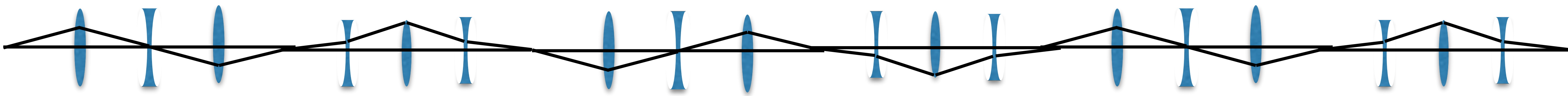
Betatron Oscillation



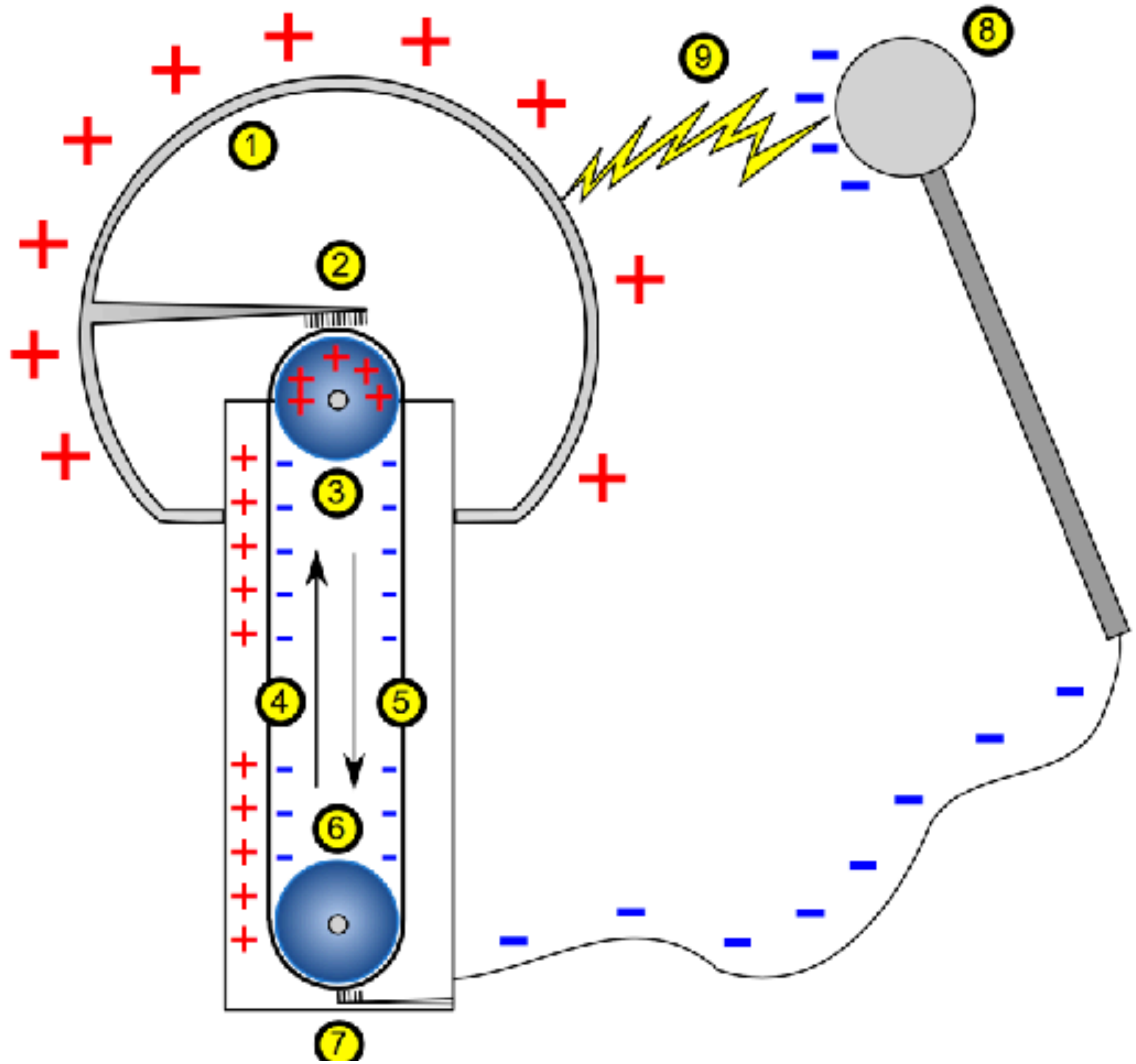
- The principle of strong focusing allows us to transport charged particles for long distance.
- Off-centered particles will oscillate around the designed orbit while traveling.
- We call this oscillation “Betatron Oscillation”.

Acceleration by Electric Field

- DC(Static Field) ：
  - Van de Graaff Type：Using mechanically moving insulated belt to accumulate charges on the electrode.
  - Cockcroft–Walton Type：Cockcroft–Walton multiplier circuit consists of capacitors and diodes. It turns input AC(or pulsed DC)
- RF Field(Alternating fields):

The Cockcroft–Walton Accelerator in KEK-PS.

Van de Graaff Accelerator

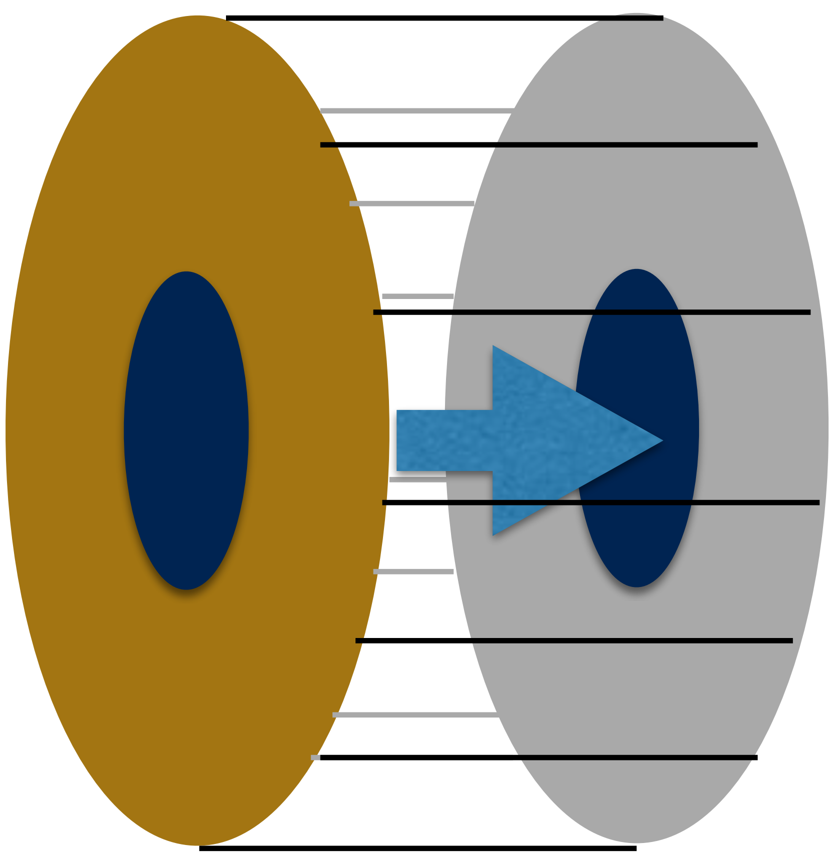


Acceleration by Electric Field

- DC(Static Field) ：
- RF Field(Alternating Field):
  - Main stream method in modern accelerators.
  - Supply Radio frequency wave to Cavities. Accelerate charged particles using the electric field within cavities.
  - Synchronization of the RF frequency with the particles should be considered.

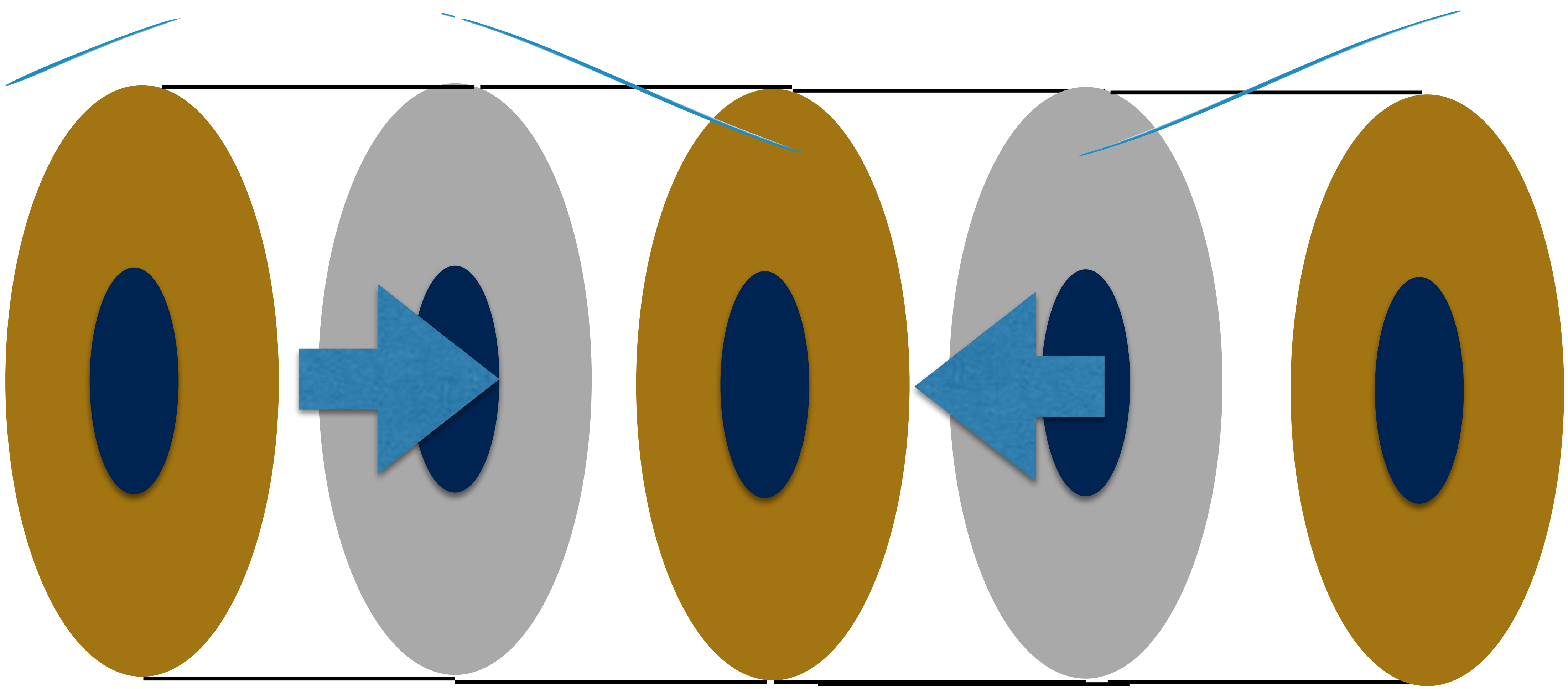
The Cockcroft–Walton Accelerator in KEK-PS.

RF Acceleration



Radio Frequency wave(Electric-magnetic wave) inside a cavity create alternating Electric field.

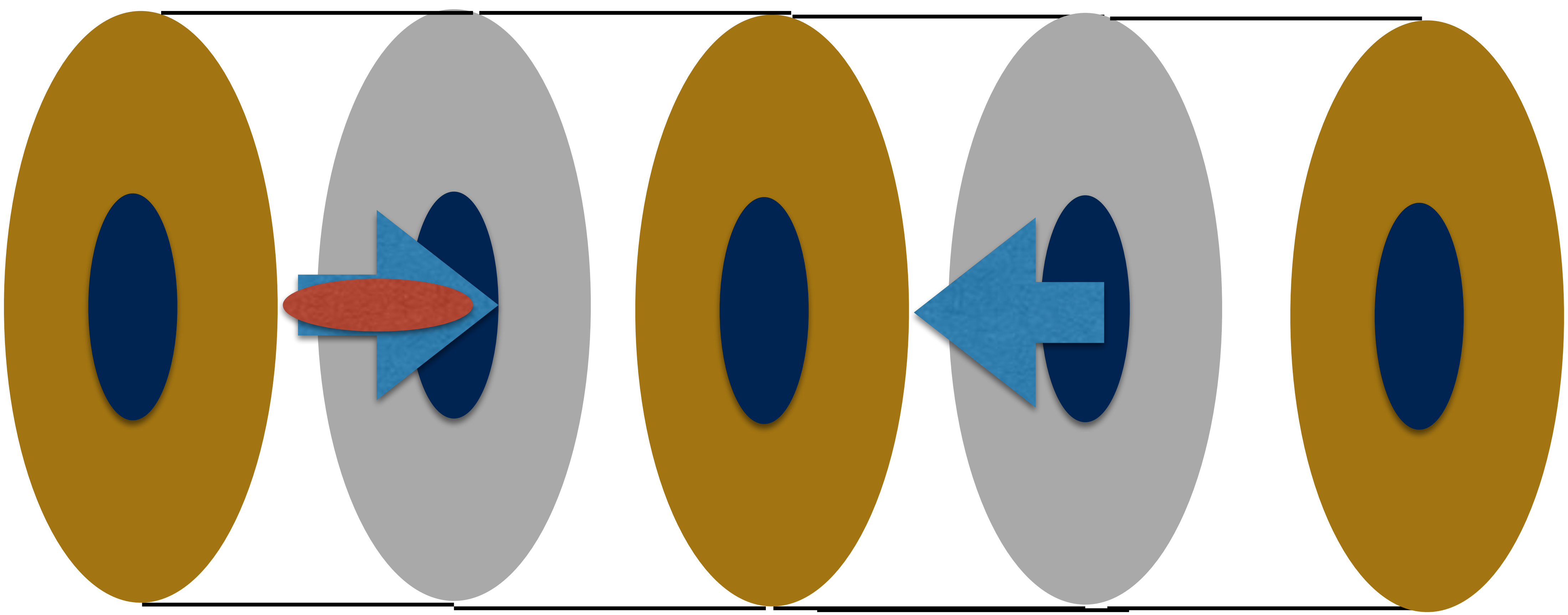
RF Acceleration



Radio Frequency wave(Electric-magnetic wave) inside a cavity create alternating Electric field.

Combining Cavities for efficient acceleration.

RF Acceleration



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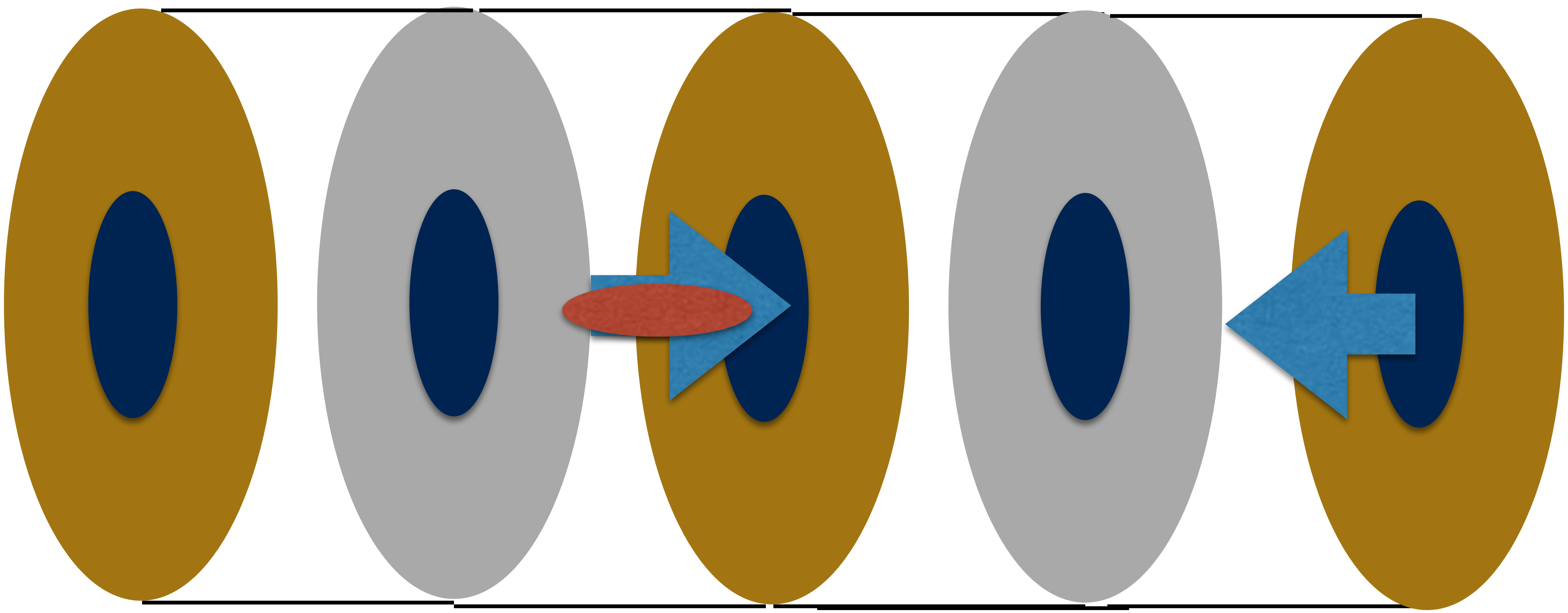
RF Acceleration



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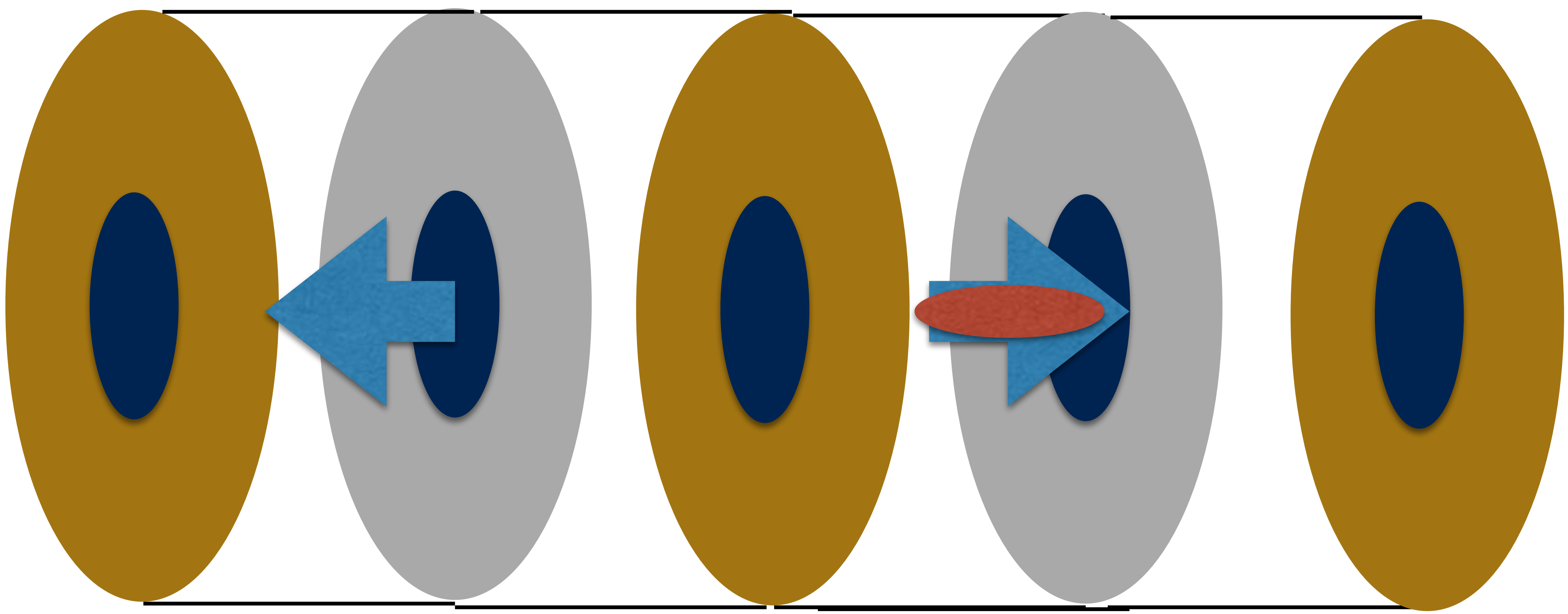
RF Acceleration



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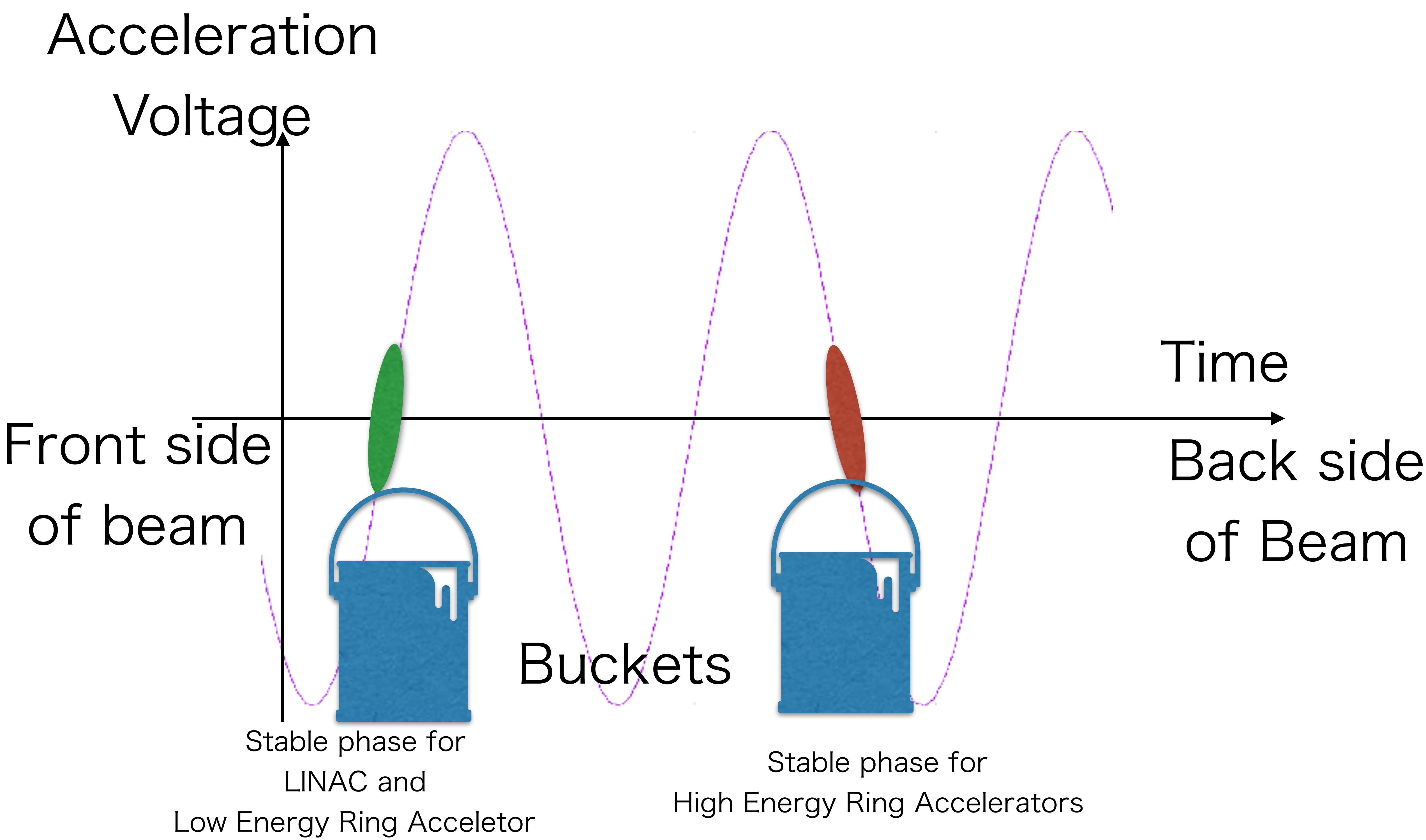
Combining Cavities for efficient acceleration.

Phase stability



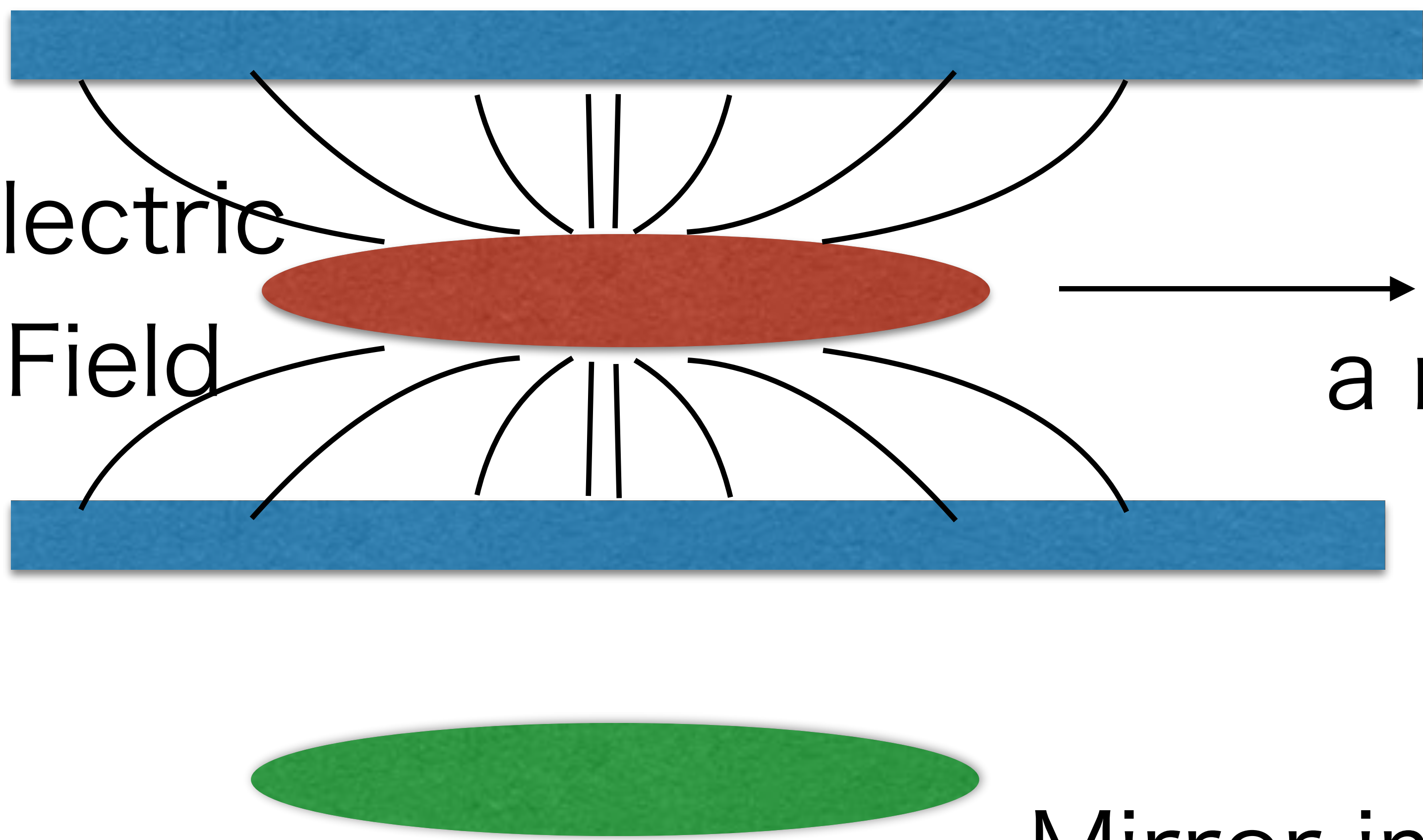
Beam Stabilities
and
Oscillation

- Beam in a ring(periodic structure) accelerators oscillate around stable orbit/phase.
  - Strong Focusing : Betatron Osc.
  - phase stability : Synchrotron Osc.

Beam Instabilites.

- Coupling between these oscillations can cause instabilities when a resonance condition mets.
    - Space Charge Effect: Electric-magnetic fields generated by surrounding particles in a beam.
    - Wake field: Electric-magnetic fields generated and left in the accelerator by beam.
- non-linear forces can also leads to resonances between these oscillation.
    - Edge fields of magnets, Errors in magnet, higher pole magnet for correction.

Space Charge Effect



each charged particle in the beam are affected by Electric field from mirror image of the beam

Stabilization

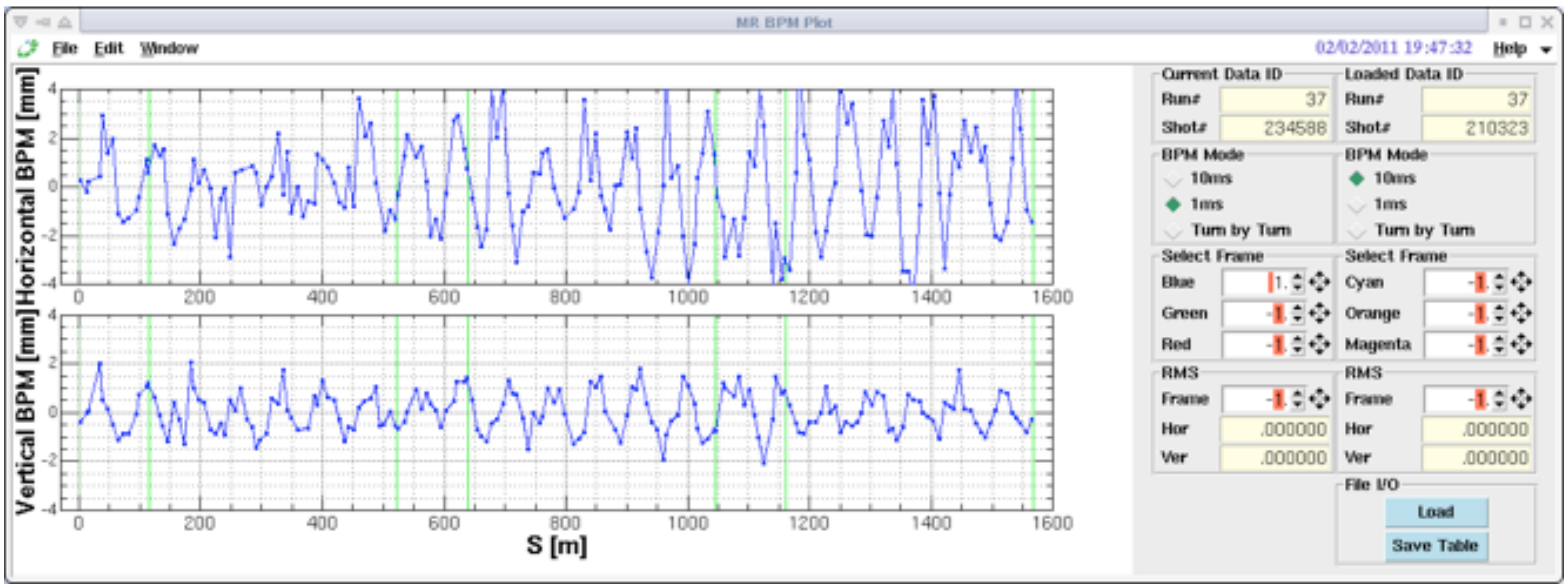
- As Beam current and Beam power increase, beam instability caused by space charge effect, wake field effect and other source become more important.
- (Possible) cures against beam instabilities
  - Introduction of decives :Higher order cavity, smoothed beam pipes etc.
  - Suppression of instability by Fast Feedback
  - Reduce beam resonances: Optics correction/Higher order component correction.

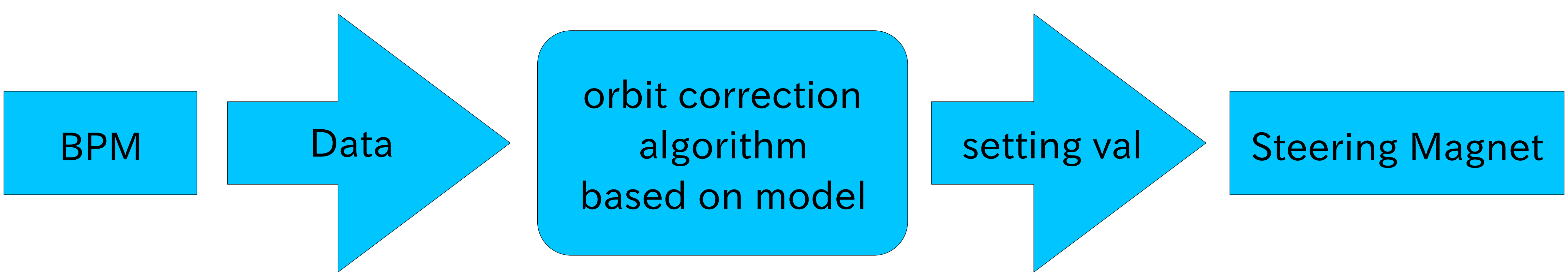
Example of beam control

- Closed orbit correction
  - Errors in magnets caused offset of averaged orbit from design orbit.
  - using steering magnets, this orbit error can be corrected.
  - In J-PARC MR, 186 Beam position monitors and 93 steering margets are used this this correction.

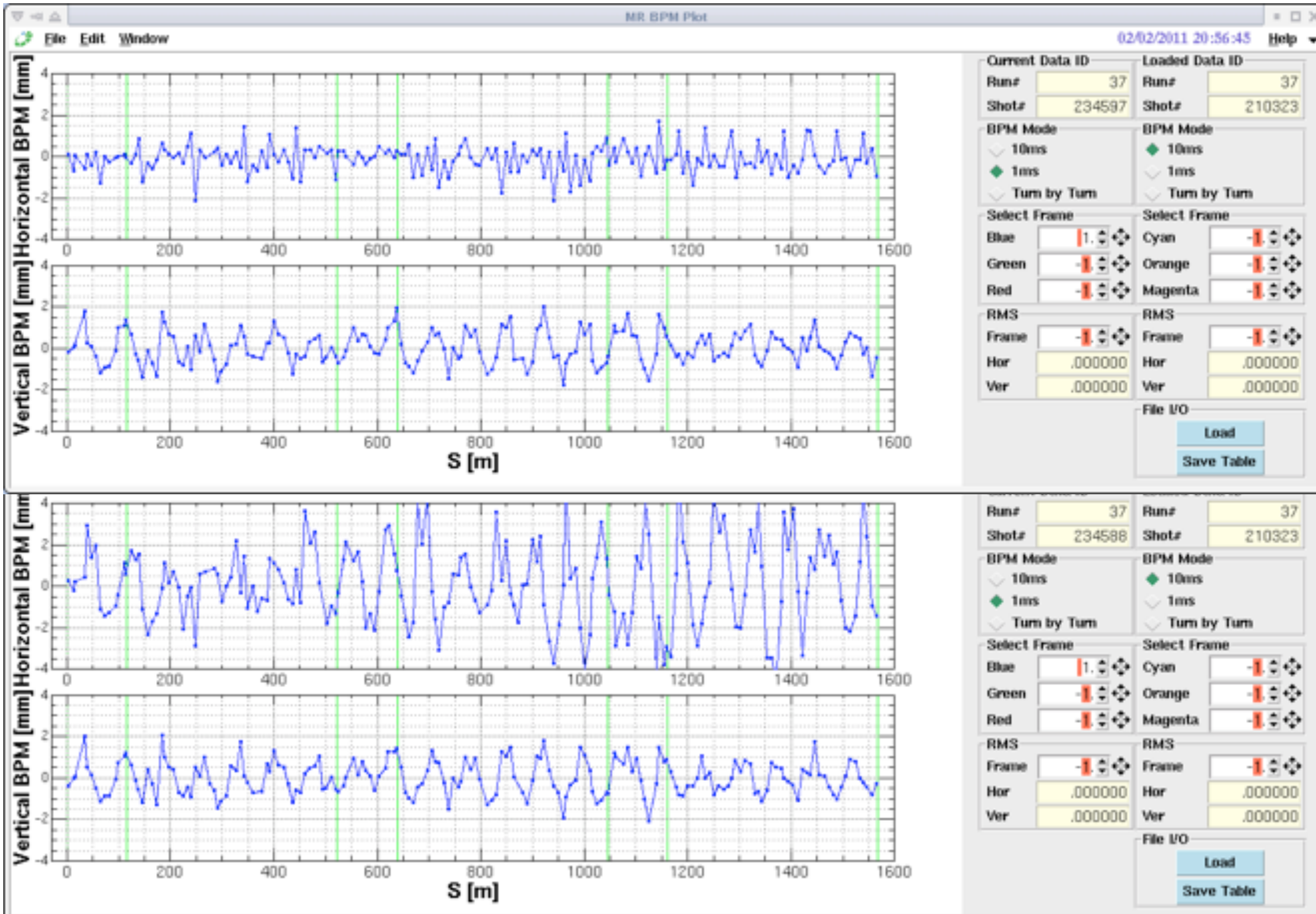
Closed Orbit Correction

Orbit data before correction





After beam Correction



Accelerators

Vacuum System ⟹ chassis

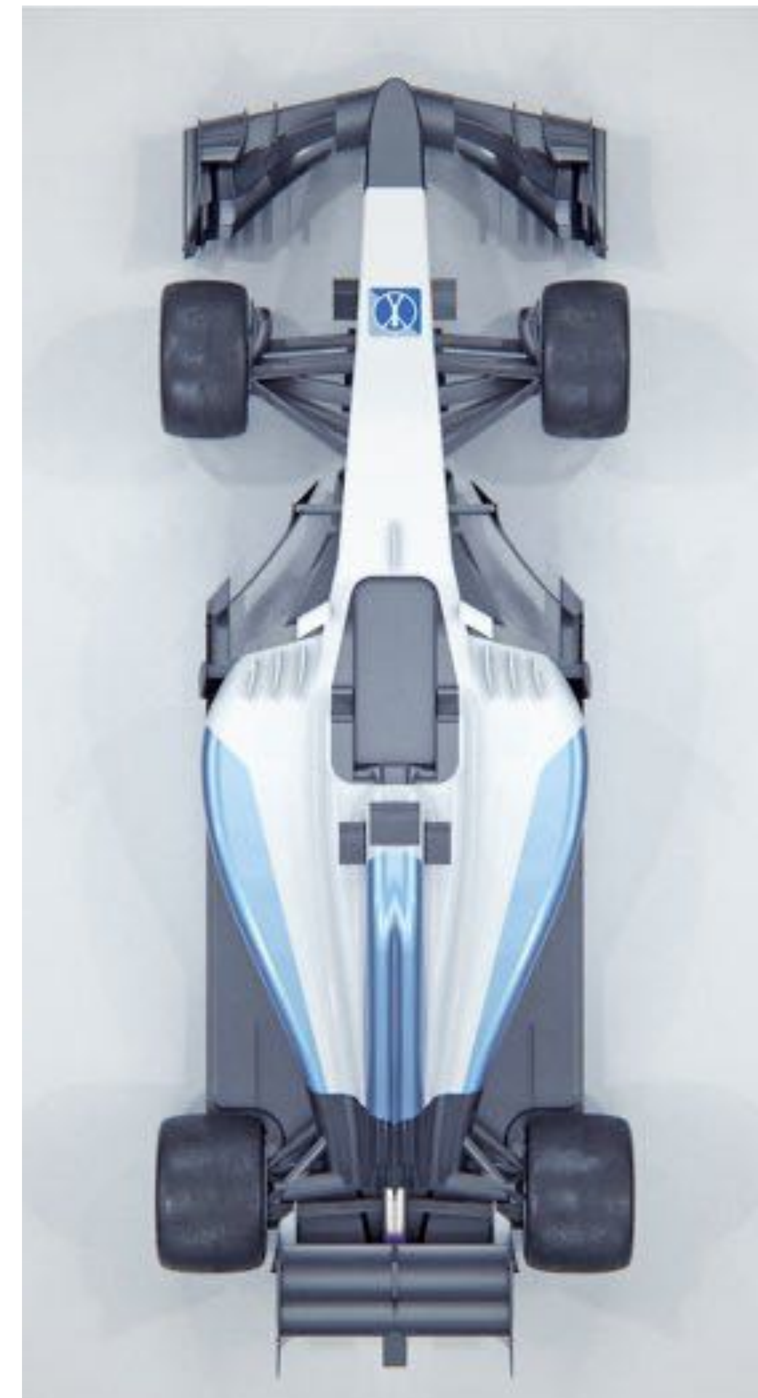
RF(EM wave) System ⟹ engine/motor

Magnets ⟹ Tires

Injection/Extraction ⟹ ?

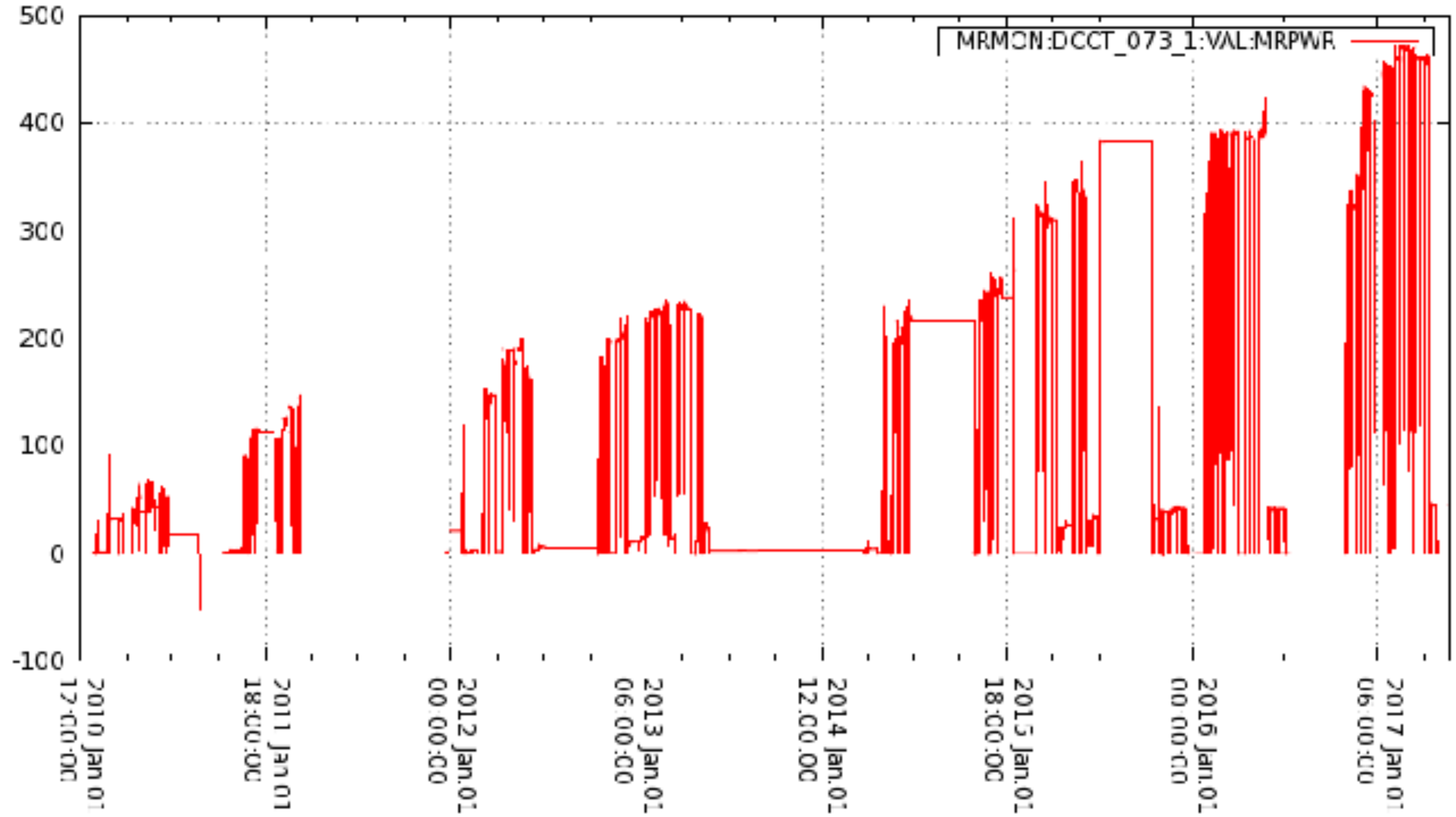
Monitors/Beam Instrumentation ⟹ Censors

Control System ⟹ Steering/Driver



Conclusion

- Wide range of Accelerator Research is essential to achieve High performance accelerator operation and Physics output.



Any Question?