FFA’22, Oxford 09/2022

# Phase-free beam acceleration with ICZC FFA

Y.Mori

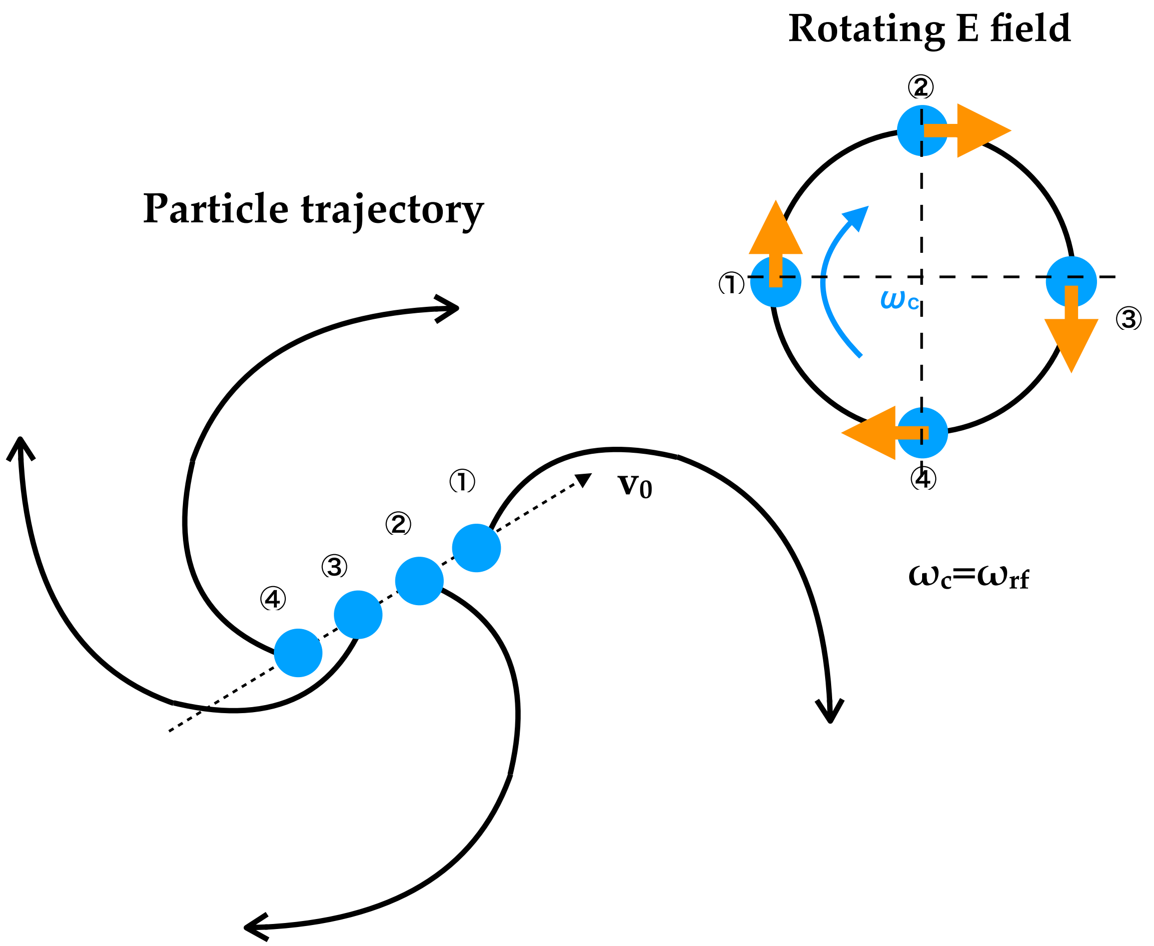
Institute for Integrated Radiation and Nuclear Science
Kyoto University

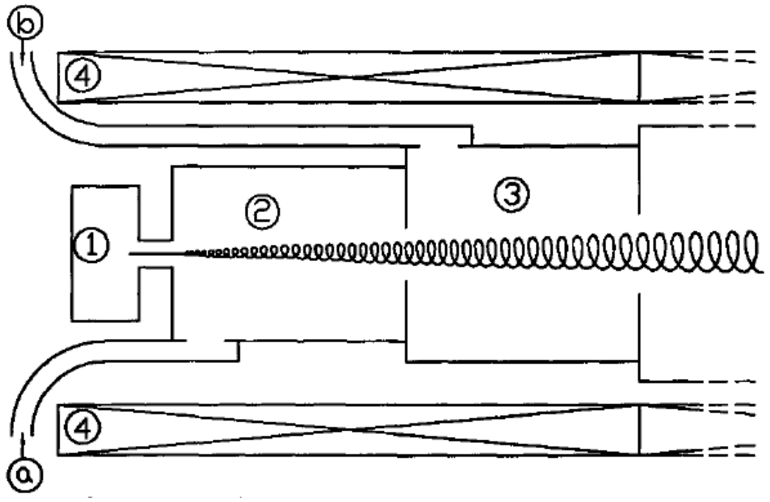
# Introduction

- **High energy and high intensity hadron accelerators**
  - Production of intense secondary particles:neutron, muon, unstable nuclei
    - Particle physics, Nuclear physics, solid-state physics, etc.: JPARC, ISIS, SNS, ESS, RIBF, FRIB
    - Beam power ~ 1MW
  - Atomic energy production
    - Nuclear transmutation of radioactive wastes: ADS
    - Nuclear fusion: Muon catalyzed fusion, Neutral beam injection for plasma heating
    - Beam power ~ >10MW
- **New scheme : Phase-free beam acceleration with ICZC FFA**
    - ICZC FFA : IsoChronous and Zero-Chromatic Fixed Field Accelerator

# Phase free (PF) acceleration

- **One of the most difficult issues to reach a beam power of >10-100 MW is how to control a space-charge force.**
  - In RF accelerators, particles are longitudinally localized/ bunching around a certain RF phase, so that the longitudinal defocusing forces could induce various beam instabilities and beam losses.
- **An ideal scheme is a DC beam acceleration. → No bunched beam.**
  - But, no way in electro-static acceleration.
- **Is it possible of DC beam acceleration with RF field?**
  - Rotating (circularly polarized) RF field
    - **→ Phase-free(PF) cyclotron resonance acceleration with rotating RF field**
  - However, $\omega_c \propto 1/\gamma$, so that different frequency multi-RF cavities are required to accelerate the particles in high energy. → ‘Pulsed beam’ with the m/Δf interval for phase matching is inevitable.
  - If B increases with $\gamma$ to keep $\omega_c$ constant, a defocusing force arises.→Mirror effect
- **PF acceleration needs ICZC optics (‘IsoChronous’ and ‘Zero Chromatic’ )**



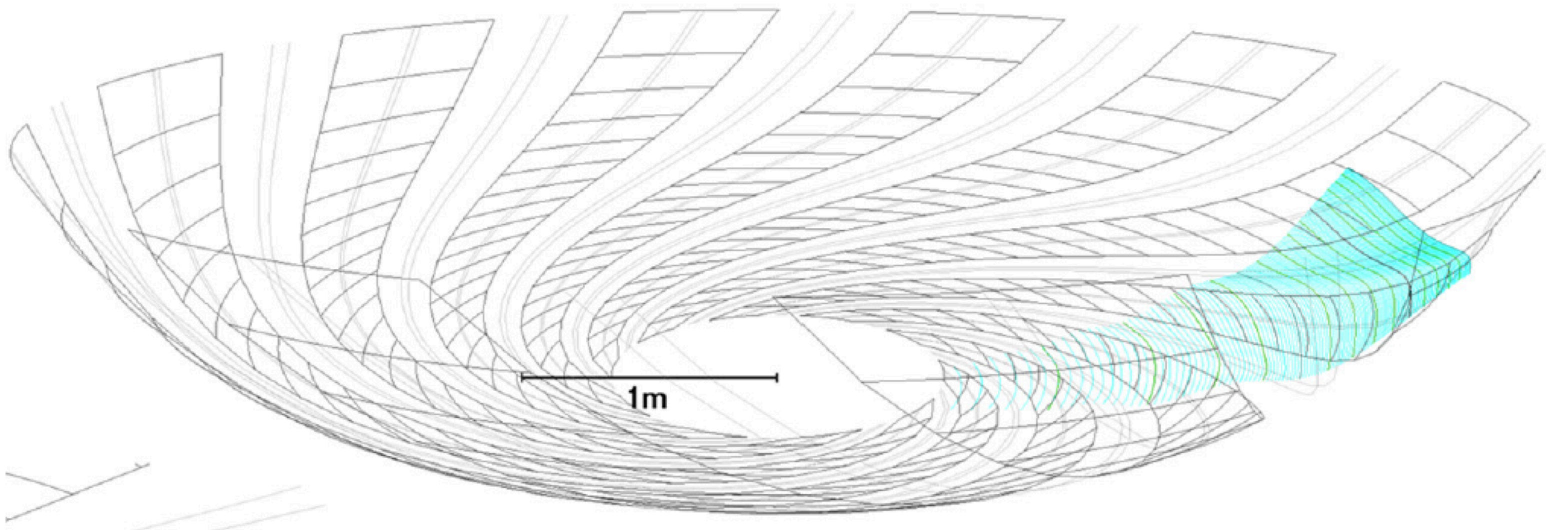


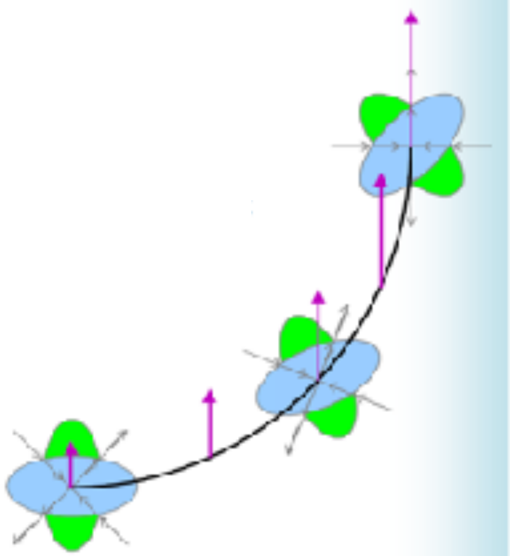
**Multi-cavity proton accelerator**

J.L.Hirshfield et al.,PRLST,5,081301(2002).

# ICZC optics for PF acceleration

- **Requirements of beam optics and dynamics in the phase-free acceleration**
  - (1) Isochronous acceleration
    - Need the constant RF frequency in acceleration, so that any phase can join the acceleration.
  - (2) Zero-chromatic optics
    - Keep the betatron tunes constant during acceleration to avoid the resonance crossing while B is proportional to γ in isochronous acceleration.
  - **Magnetic field configuration in spiral sector focusing** that satisfies these two conditions has already been studied and obtained by S. Brooks: IPAC2014.





# Requirements of ICZC optics
# -weak focusing-
## (Based on study by Stephen Brooks)

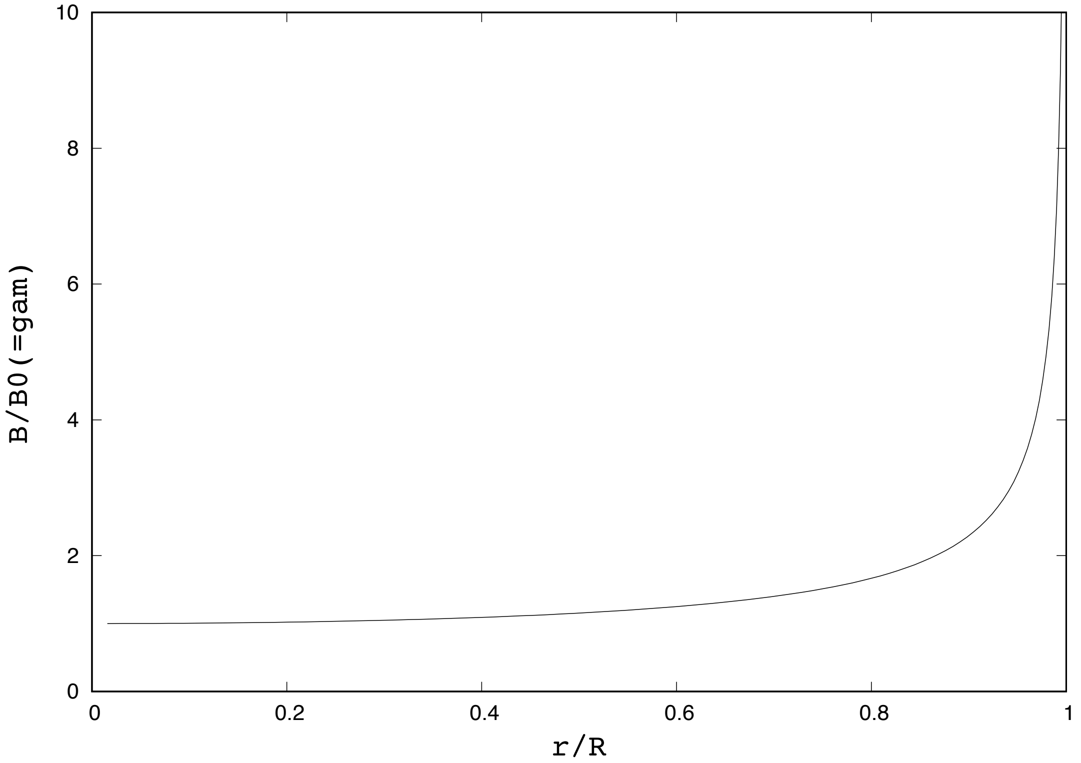
- **Phase-free acceleration by rotating RF field requires isochronous and zero-chromatic optics.**
- **(1) Isochronous criteria**

$$\omega_0 = \frac{qB}{m_0 c\gamma} = \frac{\beta c}{r} = \text{const.}$$

  - To satisfy this condition,
    - Orbit excursion: proportional to velocity
    - Magnetic field strength: proportional to energy

$$\beta = \frac{r}{R},\ r = R \text{ at } \beta = 1.$$

$$\gamma = \frac{B}{B_0},\ B = B_0 \text{ at } \gamma = 1.$$



  - Thus, the orbit excursion and the magnetic field strength are specified by an angle $\psi$ as follows.

$$\frac{B_0}{B} = cos\psi, \frac{r}{R} = sin\psi\ \ (0 \leq \psi \leq \pi/2)\,.\ \ \because \beta^2 + \frac{1}{\gamma^2} = 1.$$

- **(2) Zero chromaticity**
  - Weak focusing : strong focusing (spiral) → i.e., Brooks
  - Linearized betatron equations in dipole and rotating(angle=$\theta$) Q fields are,

$$\frac{d^2}{d\theta^2}\begin{bmatrix}x\\y\end{bmatrix}+\left[\begin{bmatrix}1\\0\end{bmatrix}+\boldsymbol{RNR^{-1}}\right]\begin{bmatrix}x\\y\end{bmatrix}=0$$

$$\boldsymbol{N}=\begin{bmatrix}-n & 0\\0 & n\end{bmatrix}\quad\boldsymbol{R}=\begin{bmatrix}\cos\theta & \sin\theta\\-\sin\theta & \cos\theta\end{bmatrix}\quad n=-\frac{r}{B_y}\left(\frac{\partial B_y}{\partial x}\right)=-\frac{r}{B_y}\left(\frac{\partial B_y}{\partial r}\right)$$

$$\boldsymbol{N^R}=\boldsymbol{RNR^{-1}}=\begin{bmatrix}-n\ cos\psi & n\ sin\psi\\n\ sin\psi & n\ cos\psi\end{bmatrix}\qquad\psi=2\theta.$$

  - Zero chromaticity

$$\frac{\partial n}{\partial p}=0.\rightarrow n=\text{const.}$$

  - Isochronous condition: r/B term of the field index can be expressed with a superposition of r-dependent and B-dependent terms as follows.

$$\frac{r}{B_y}=\frac{r}{B_0}cos\psi,\ \frac{r}{B_y}=\frac{R}{B_y}sin\psi.$$

  - Field and closed orbit

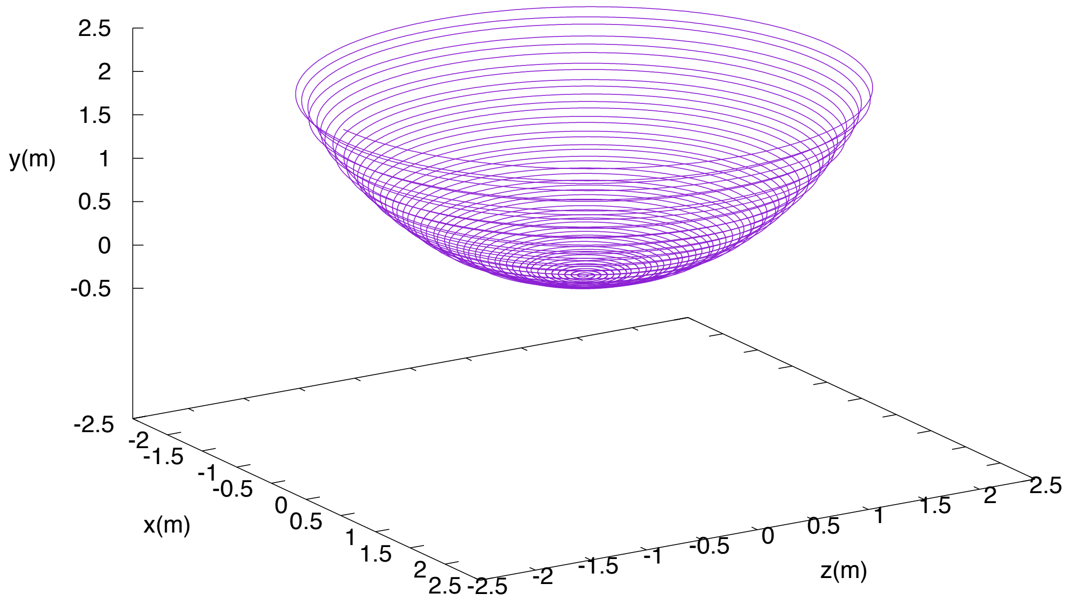
$$B_y=B_0\left[\exp\left(\frac{n}{R}y\right)-n\ln\left(\frac{r}{r_{co}}\right)\right].$$

$$\text{Here, } r_{co}=R\sin\psi,\ y_{co}=\left(\frac{R}{n}\right)\ln\left(\frac{1}{\cos\psi}\right).$$

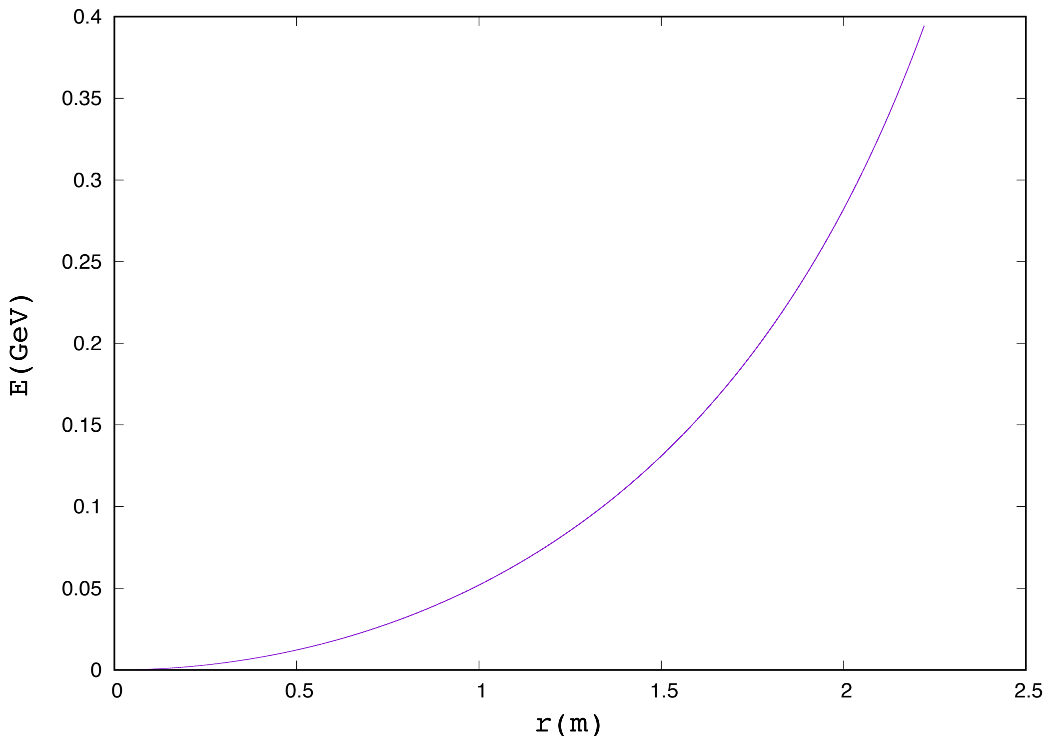
# Simulation

- **Single particle tracking simulation**
- **Leap-Flog integration**
  - B field : analytical form
  - E field : rotating RF field
  - $v_y(0)=0$ : initial velocity

| | |
|---|---|
| Particle | proton |
| Energy | 400MeV |
| Field index | n=0.5 |
| Magnetic field | 1T |
| RF electric field | 0.75MV/m |
| RF frequency | 15MHz |



**Trajectory**

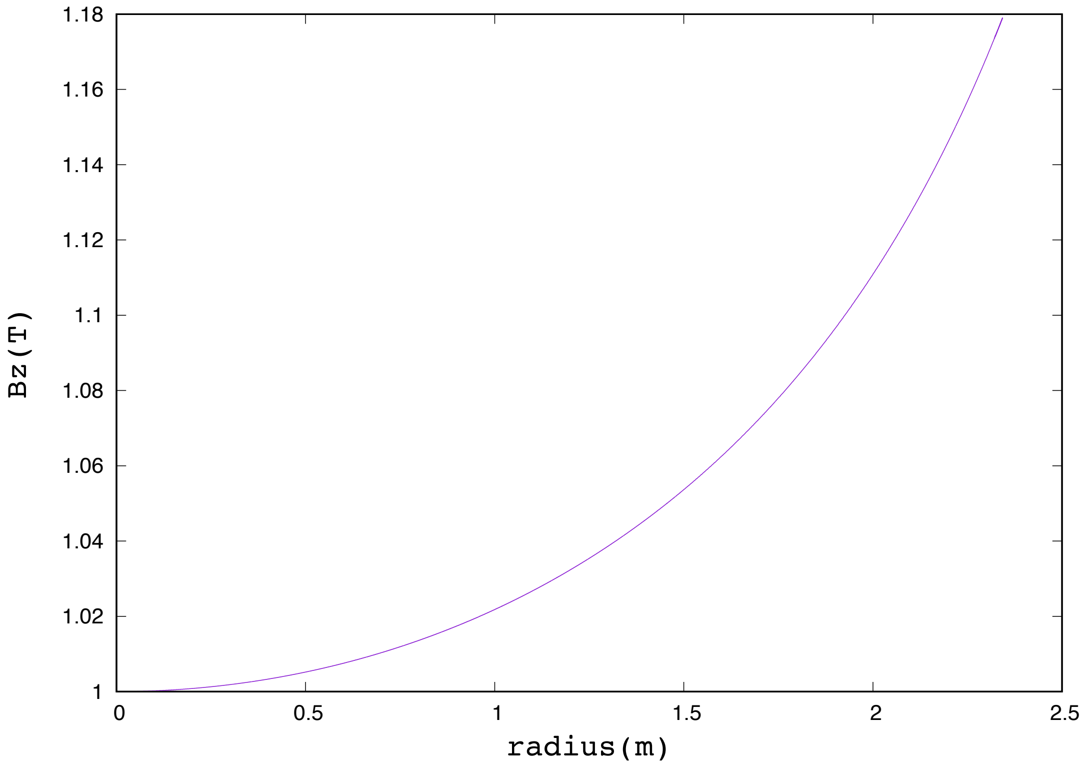


**Radius vs Energy**

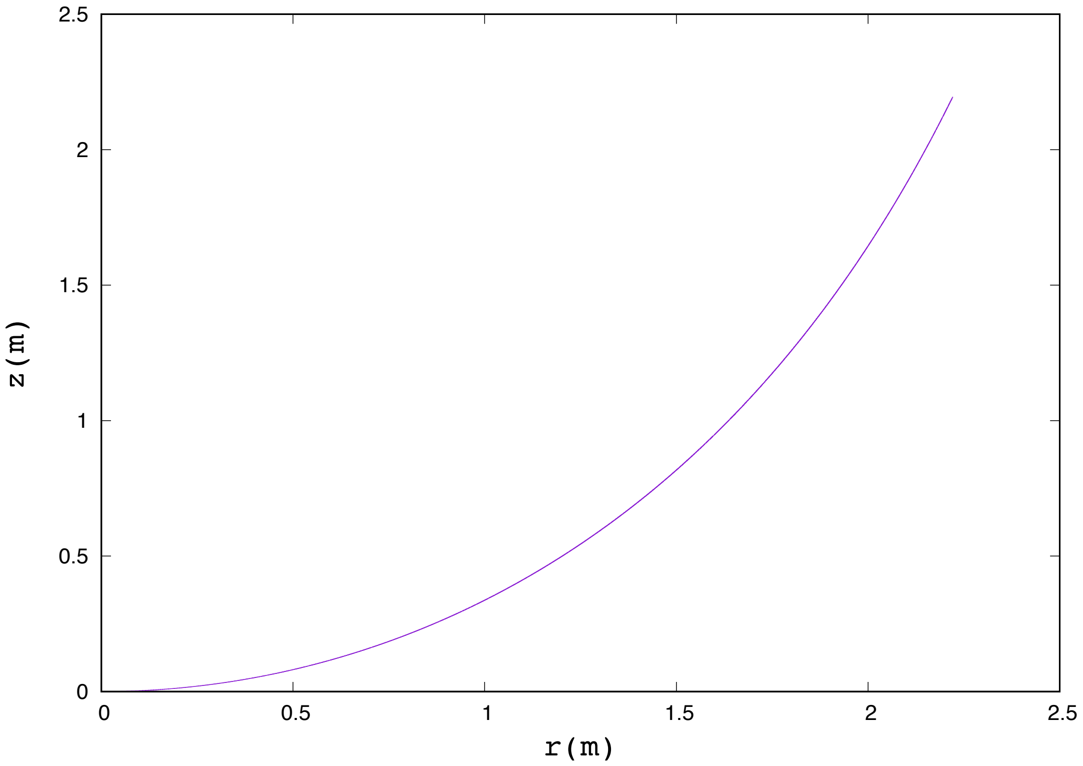
# Simulation

| | |
|---|---|
| Particle | proton |
| Energy | 400MeV |
| Field index | n=0.5 |
| Magnetic field | 1T |
| RF electric field | 0.75MV/m |
| RF frequency | 15MHz |

- **Orbit radius vs Magnetic field**



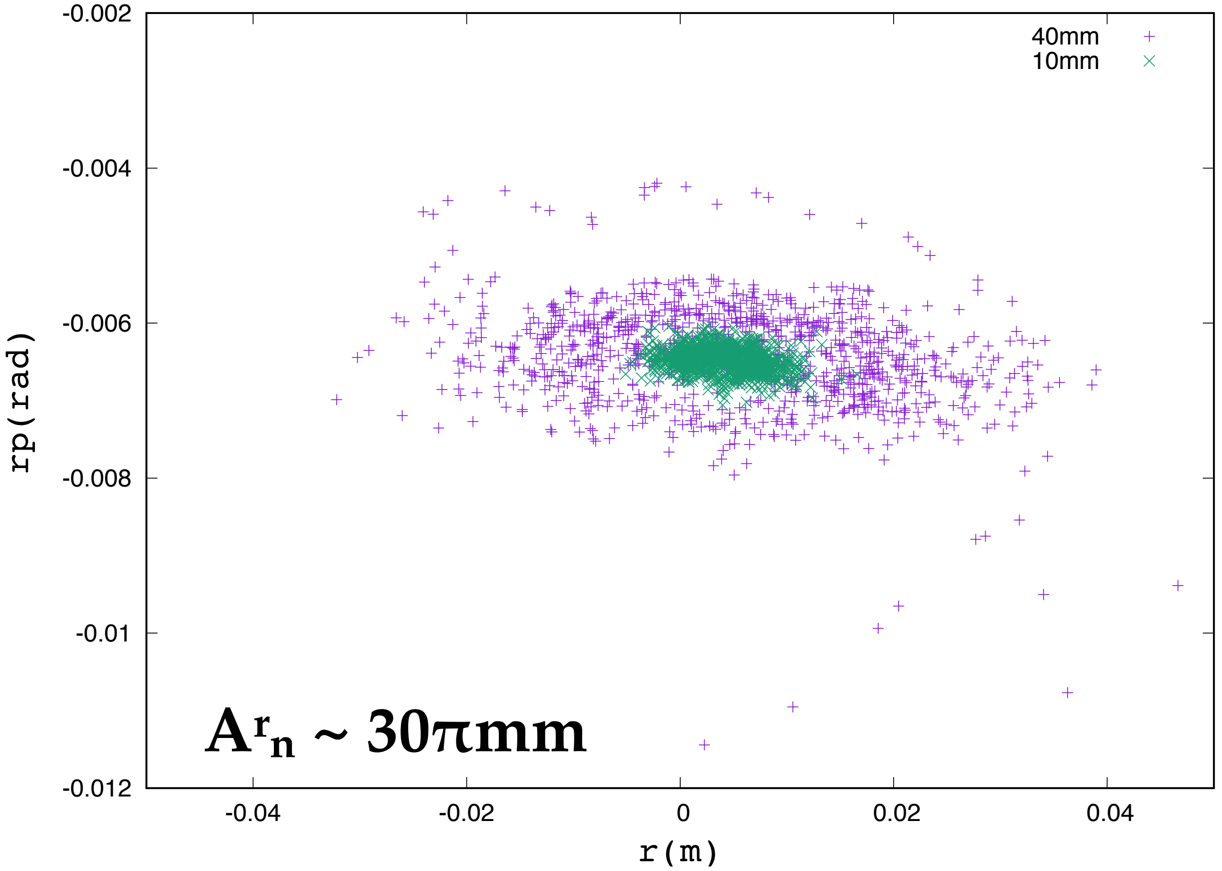
- **Orbit radius vs Orbit height**



# Emittance

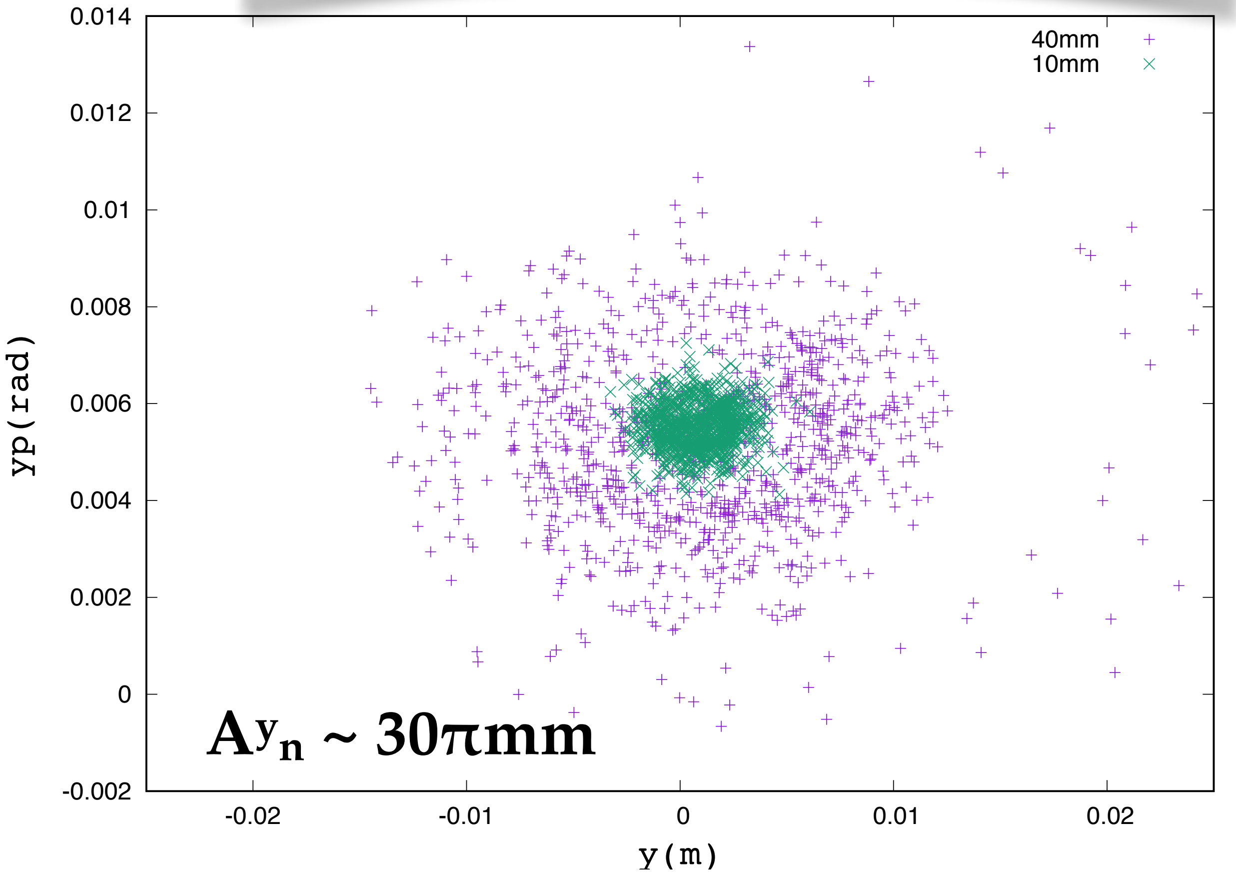
- **Initial beam distribution in real space($p_r$=$p_y$=0): Gaussian**
  - ●: σr(initial)=10mm
  - ●: σr(initial)=40mm

| | |
|---|---|
| Particle | proton |
| Energy | 400MeV |
| Field index | n=0.5 |
| Magnetic field | 1T |
| RF electric field | 0.75MV/m |
| RF frequency | 15MHz |



**$A^r_n$ ~ 30πmm**

**beam emittance: r-rp**

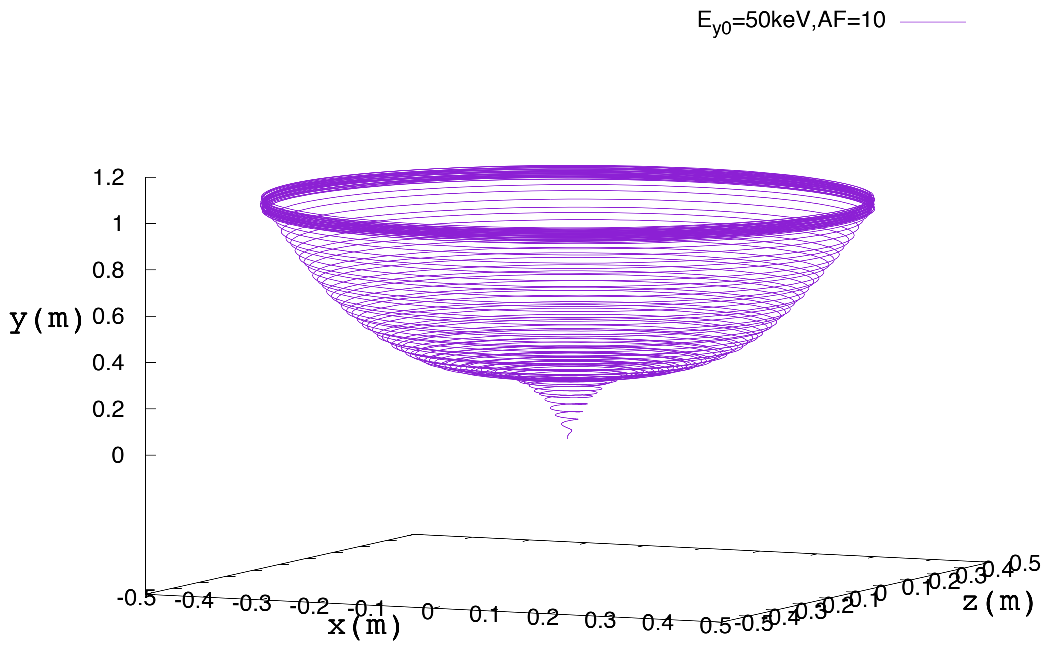


**$A^y_n$ ~ 30πmm**

**beam emittance: y-yp**

# Adiabatic capture

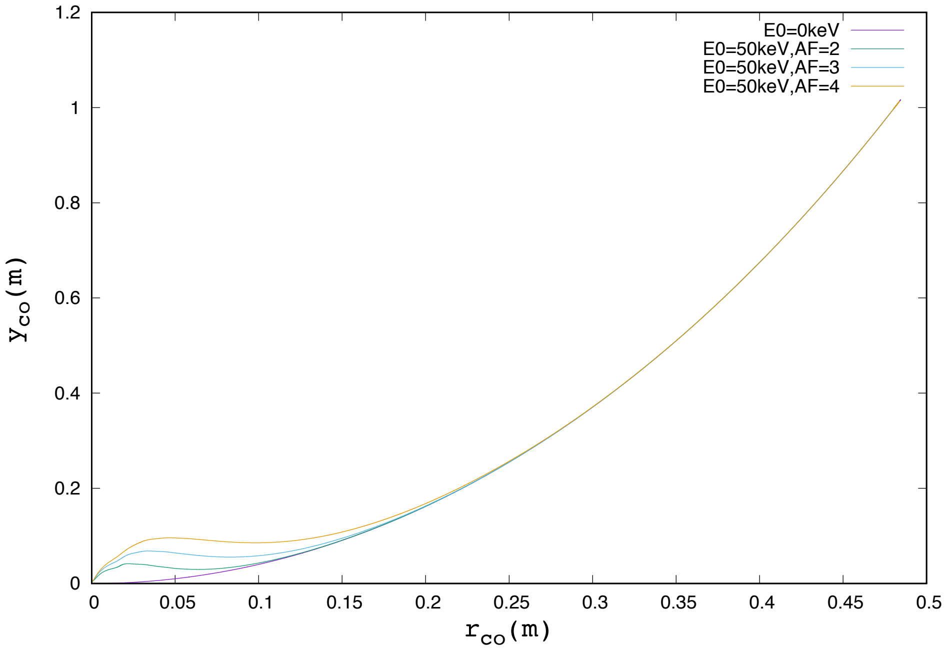
- **The beam is injected to the system axially.**
  - Initial velocity : $v_y(0) \neq 0$
- The axial particle momentum (py) can be transformed to the transverse direction adiabatically.
- We define an adiabatic factor as follows.

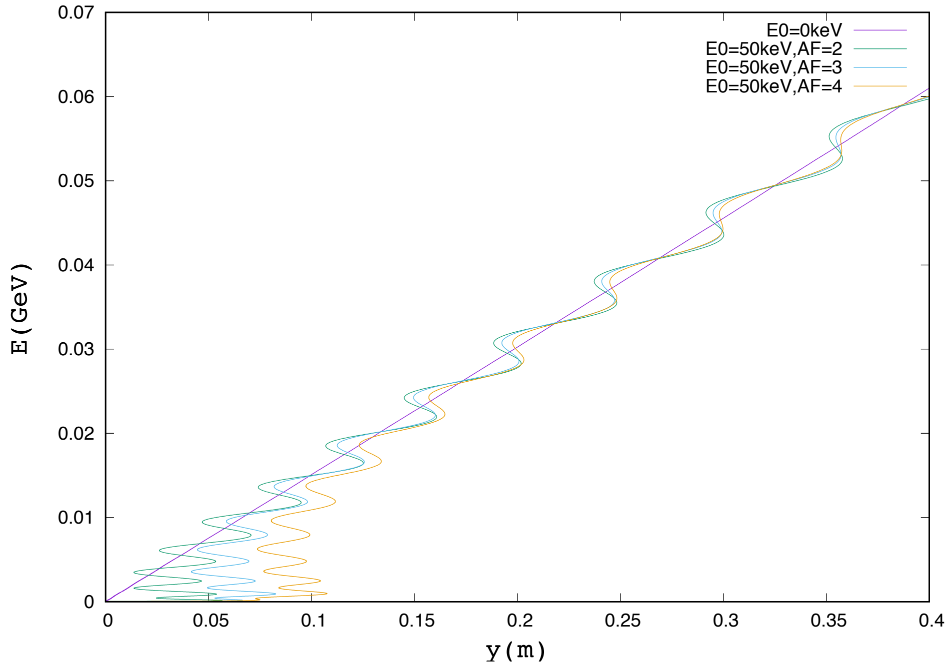


$$y_{co} = \left(\frac{R}{n}\right)\ln\left(\frac{1}{\cos\psi}\right) + v_y^d t.$$

$$v_y^d = v_y^0 \exp\left[-\frac{v_r}{v_y^0}\frac{1}{\alpha}\right]$$

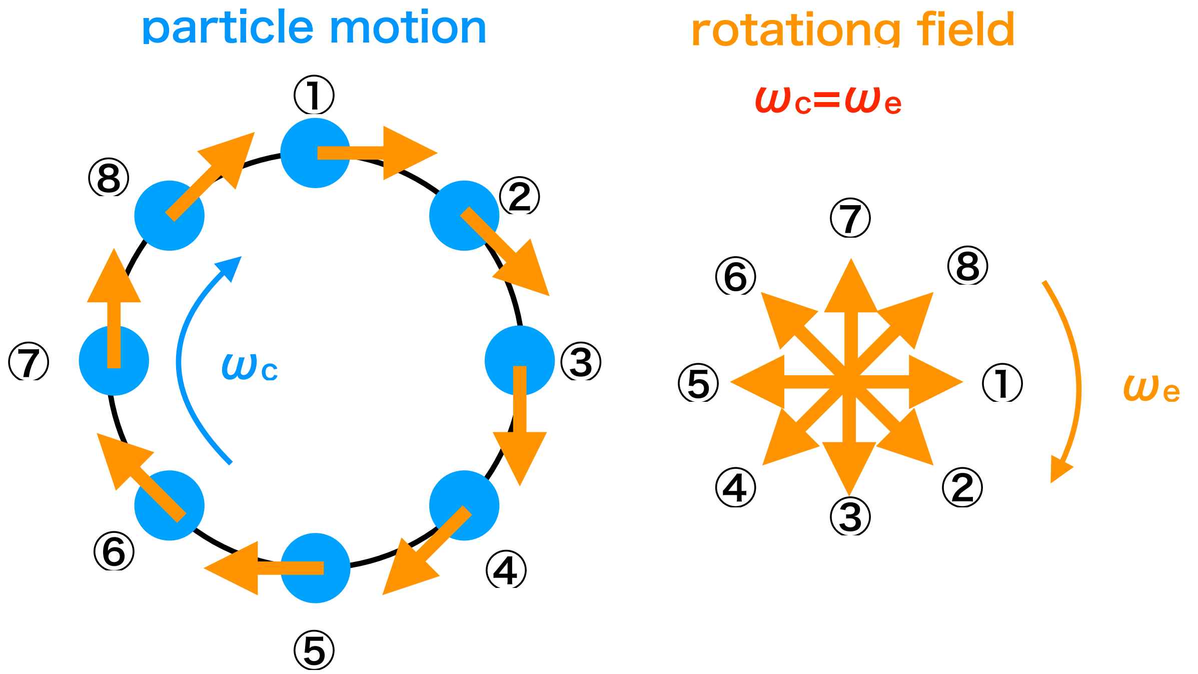
. Here, $\alpha$ is adiabatic factor.



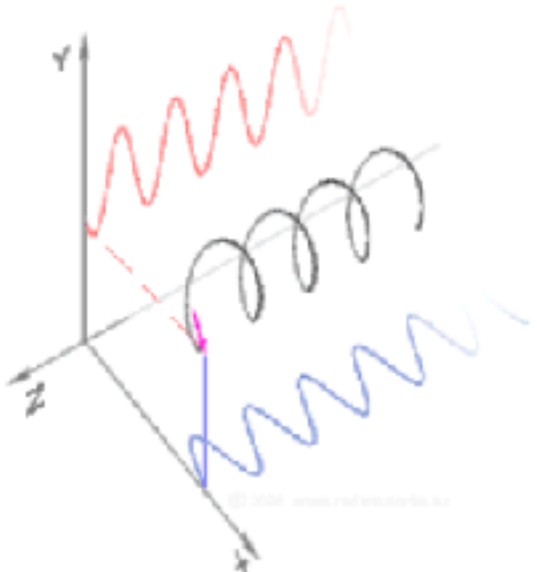


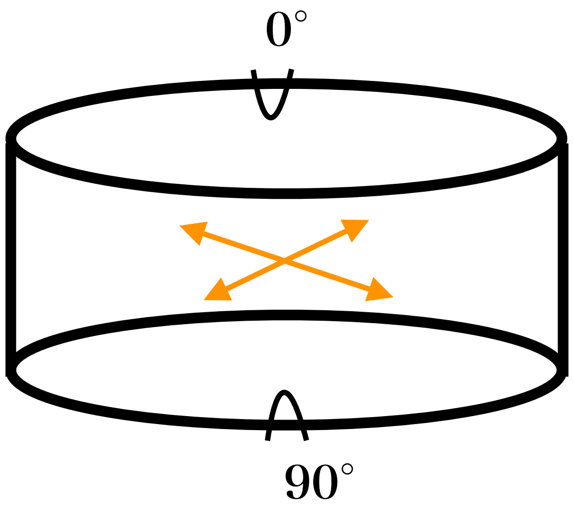
# Rotating (circularly polarized) RF field

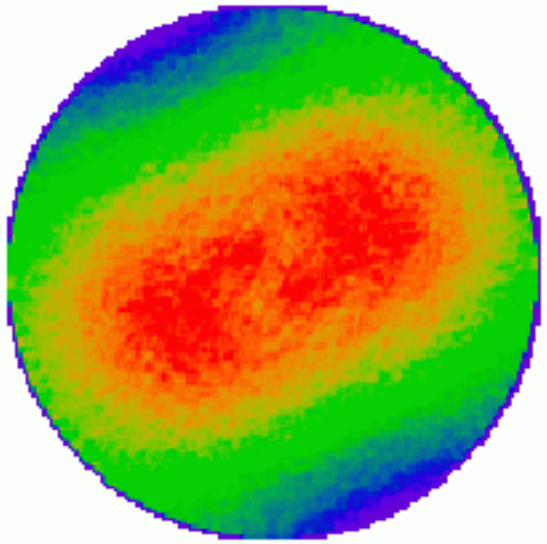
- **Rotating RF field with a cyclotron resonance acceleration**



- **How to make a rotating RF field**
  - Superposition of two linear polarized fields, one of which is 90 degrees phase difference to another.

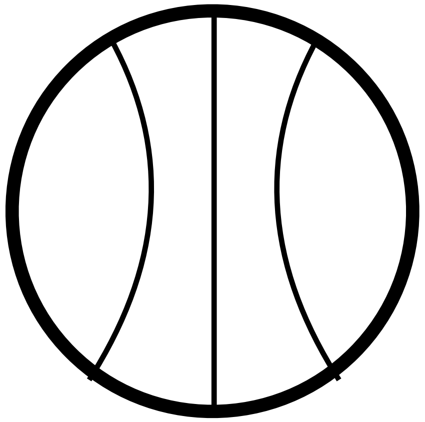




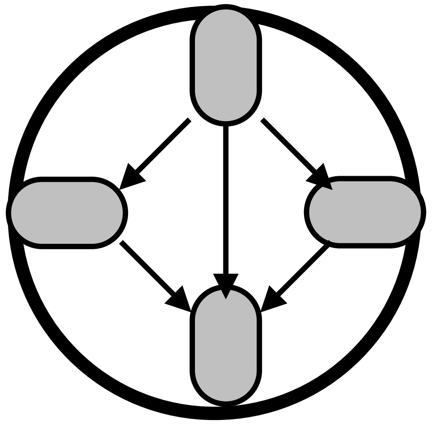


# Rotating RF field

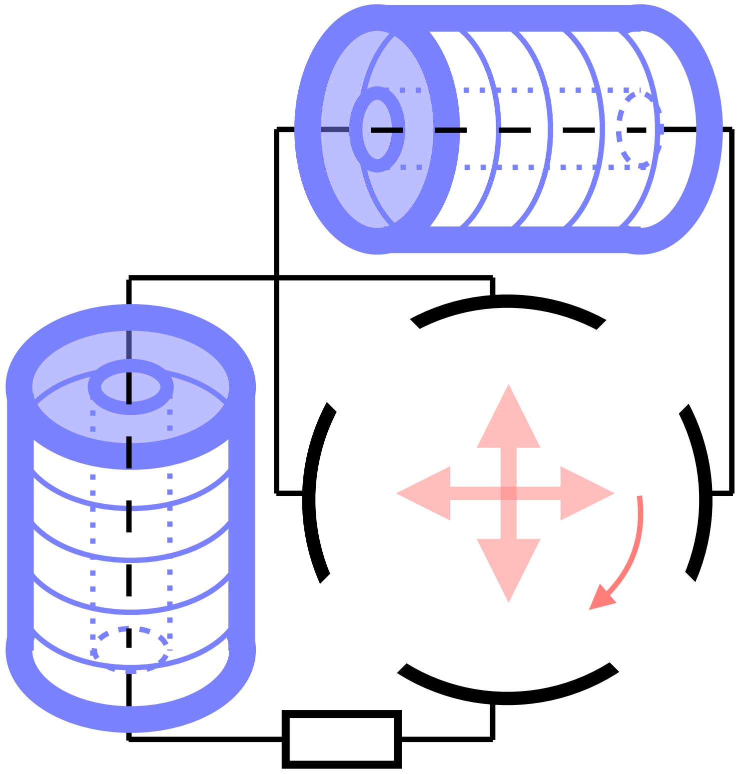
- **Air-core cavity**
    - TE11/TE11-ridge mode
    - RF frequency : $f_{rf}$~76MHz (B=5T for proton, B=10T for deuteron)
    - High RF field strength: ~MV/m
    - Decoupling between dipole and quadrupole modes, especially for a ridge mode.
- **MA loaded cavity(resonator)**
    - RF frequnecy : $f_{rf}$~15.3MHz (B=1T for proton, B=2T for deuteron)
    - Low RF field strength : ~100kV/m
    - LC resonator : High-Q MA(cut-core) as inductance(external)



TE11



TE11-ridge



# Summary

- **Possibility of the phase-free RF accelerator with isochronous and zero-chromatic (ICZC) optics are studied.**
- **Using a rotating (circularly polarized) RF field with ICZC optics, a cw (DC) beam acceleration with no-bunching can be possible and relax space-charge defocusing effects.**
- **This type of hadron accelerators could provide a large beam power and be useful for production of intense secondary particles.**
- **Critical technique issues are how to make a rotating RF field and a magnetic field of ICZC optics.**
- **Clearly, design computations, and construction and operation of a prototype should be carried out.**