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# 2-beam FFAG collider for Muon Catalyzed Fusion

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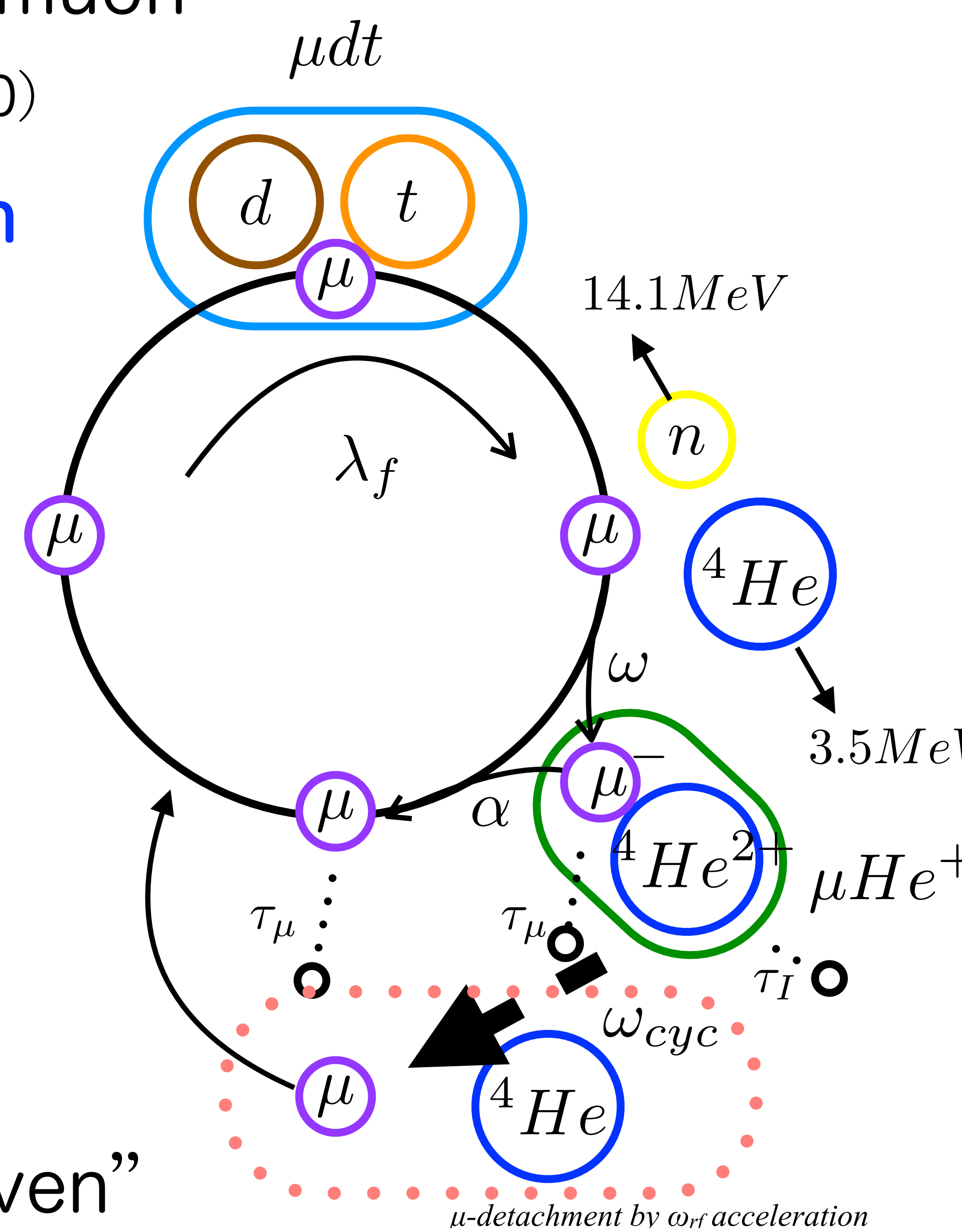
# MuCF for energy production -break even-

- MuCF break-even (Output>Input)condition
  - Muon production energy cost ~<3GeV/muon
    - D-T fusion output energy(~20MeV) x chain cycles(~150)
- Muon produced by hadron accelerator with fixed target
  - Beam energy : ~1GeV/u
  - Muon cost(fix.target) : 5~6GeV/muon
- Muon production with collider
  - Beam energy
    - E~300MeV/u
  - Muon cost
    - 1.5-2GeV/muon(collider) → "Break Even"

>2

$$\sqrt{s} \simeq 2.16GeV$$

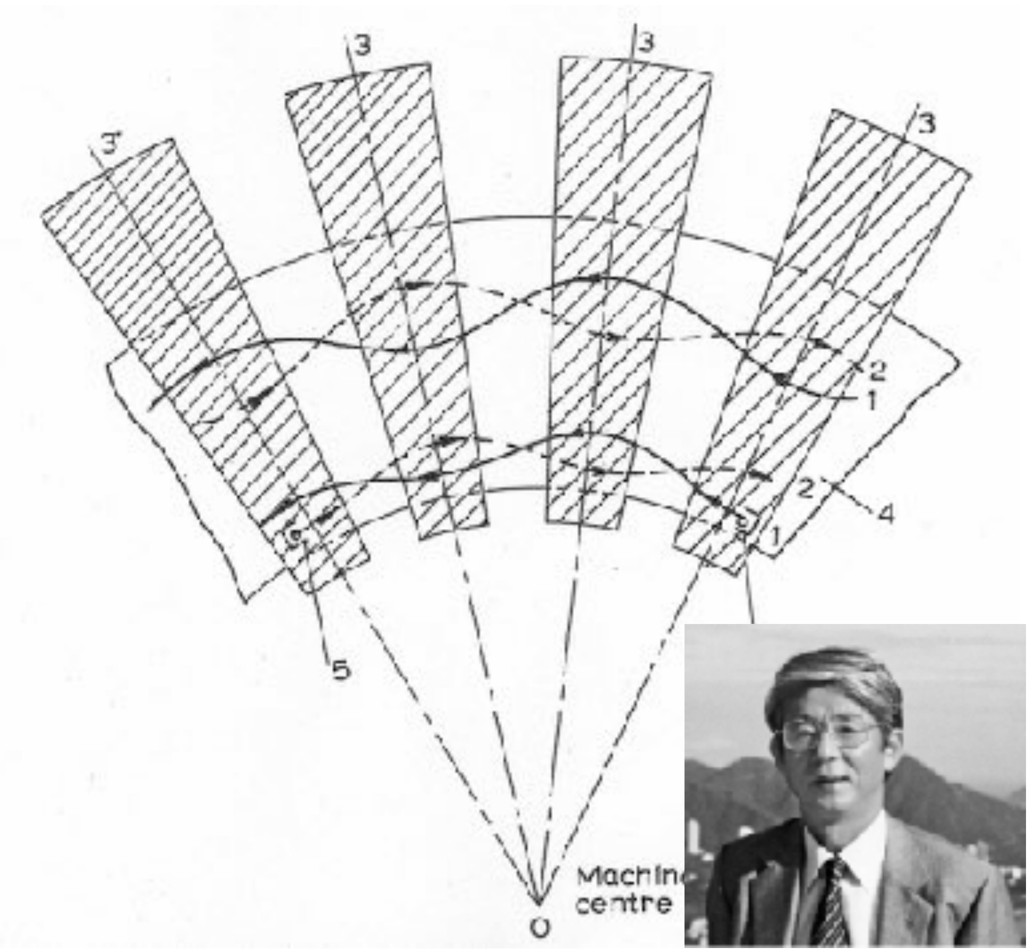


# Hadron Collider for Muon Production

- Requirements
  - Same charge state particle collider
  - Particle : neutron-rich hadron(cf. triton)
  - Energy : >140MeV/u : N-Δ resonance $\sqrt{s} \simeq 2.16GeV$
  - High luminosity : cf. L=$10^{37}$cm$^{-2}$s$^{-1}$ → Eout~>1kW
- Problems
  - Circulating beam current : >100kA →Instabilities
- 2-ring collider(ordinary way) is difficult.

# 2-beam FFAG collider

- Scaling FODO singlet FFAG
  - Exist of stable orbits of counter circulating beams of identically charged particles
    - T.Ohkawa:"Two-beam Fixed Field Alternating Gradient Accelerator",Rev.Sci.Instr.vol29,1958,pp108-117
- Scaling singlet-FODO FFAG
  - Strong focusing
  - Scaling:zero chromaticity
    - Similar closed orbits for different p.
  - Large luminosity
    - Many colliding points :2 for every FODO cell
  - Free from beam-wake instability
    - Averaged beam current is zero looking from the beam duct.

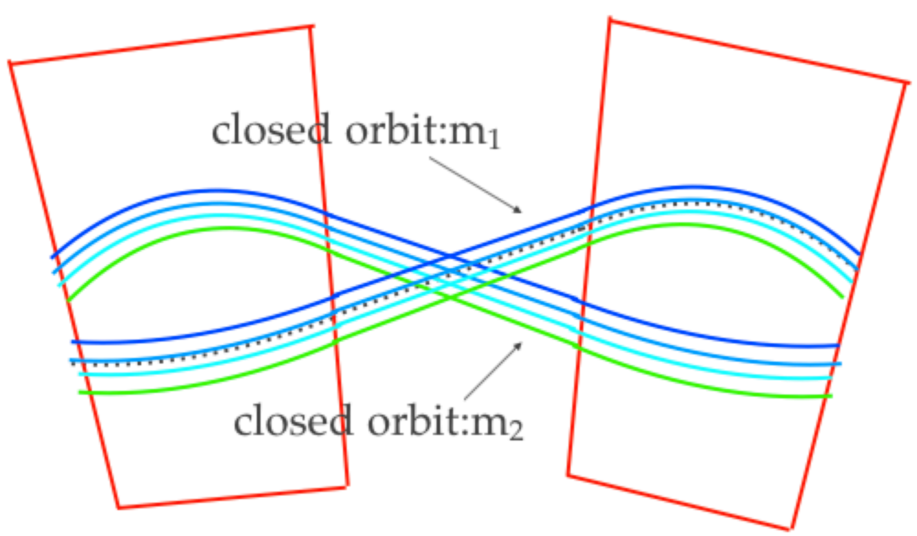


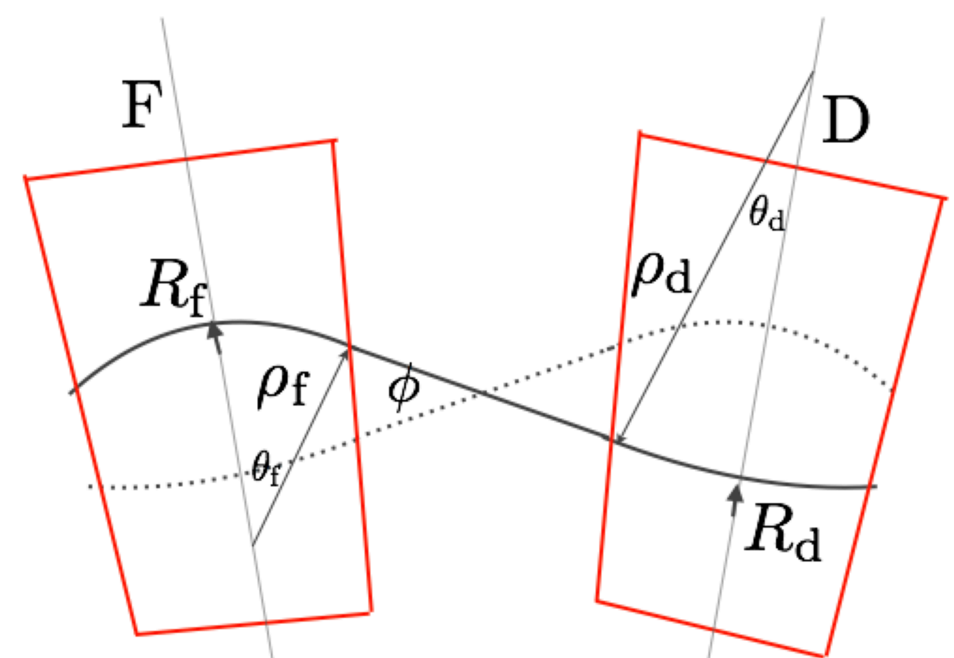
# 2-beam FFAG collider for $\mu^-$ production -triton-triton-

- Characteristics
  - E=147-190MeV ($\sqrt{s}$~2.17-2.26GeV/u)
    - Many closed orbits!
- Beam optics design
  - Linear approximation

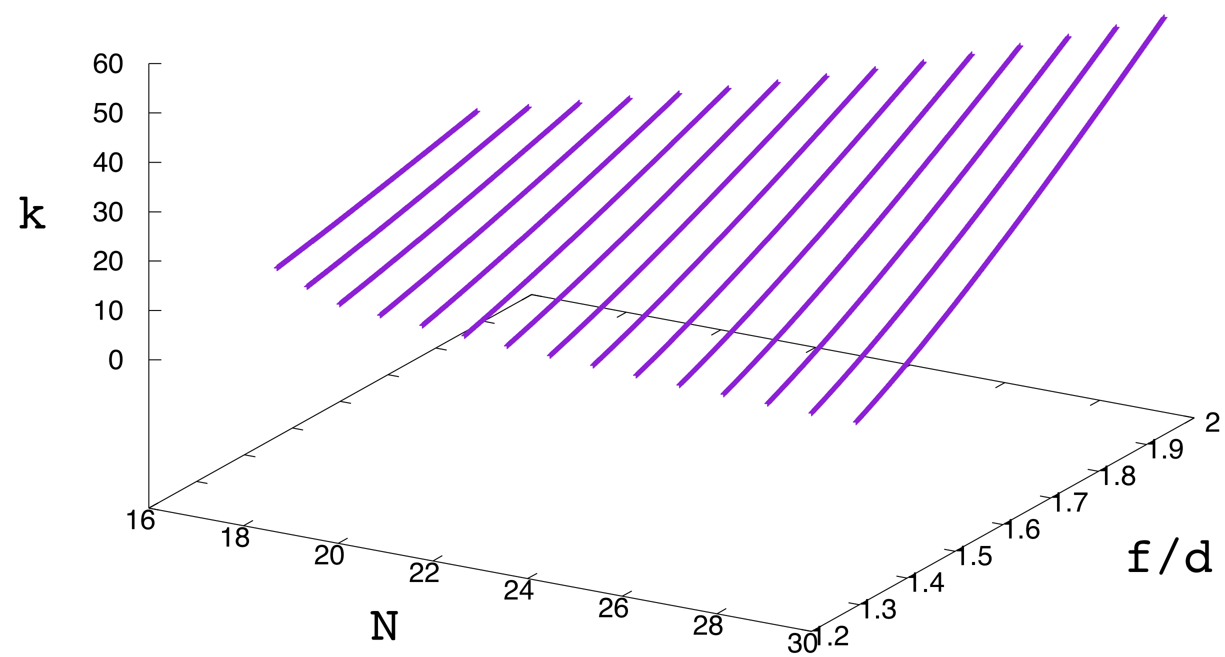
$$k = -ln\left(\frac{R_f}{R_d}\right)/ln\left(\frac{\rho_f}{\rho_d}\right)$$

| | |
|---|---|
| particle | Triton(A=3,Q=1) |
| lattice | 2-beam FODO |
| energy | 147-190 MeV/u |
| √s | 2.17-2.26GeV/u |
| radius | 16-16.4m |
| number of cells | 20 |
| opening agngle(F) | 3.375 deg. |
| opening angle(D) | 3.375 deg. |
| field index k | 11 |
| bend angle ratio $\theta_f/\theta_d$ | 1.548 |
| hor. tune Qh/cell | 0.270 |
| ver. tune Qv/cell | 0.277 |
| Rf/Rd | 1.037 |
| magnetic field B0 | 2.0T |
| half collision angle Φ | 0.383rad |

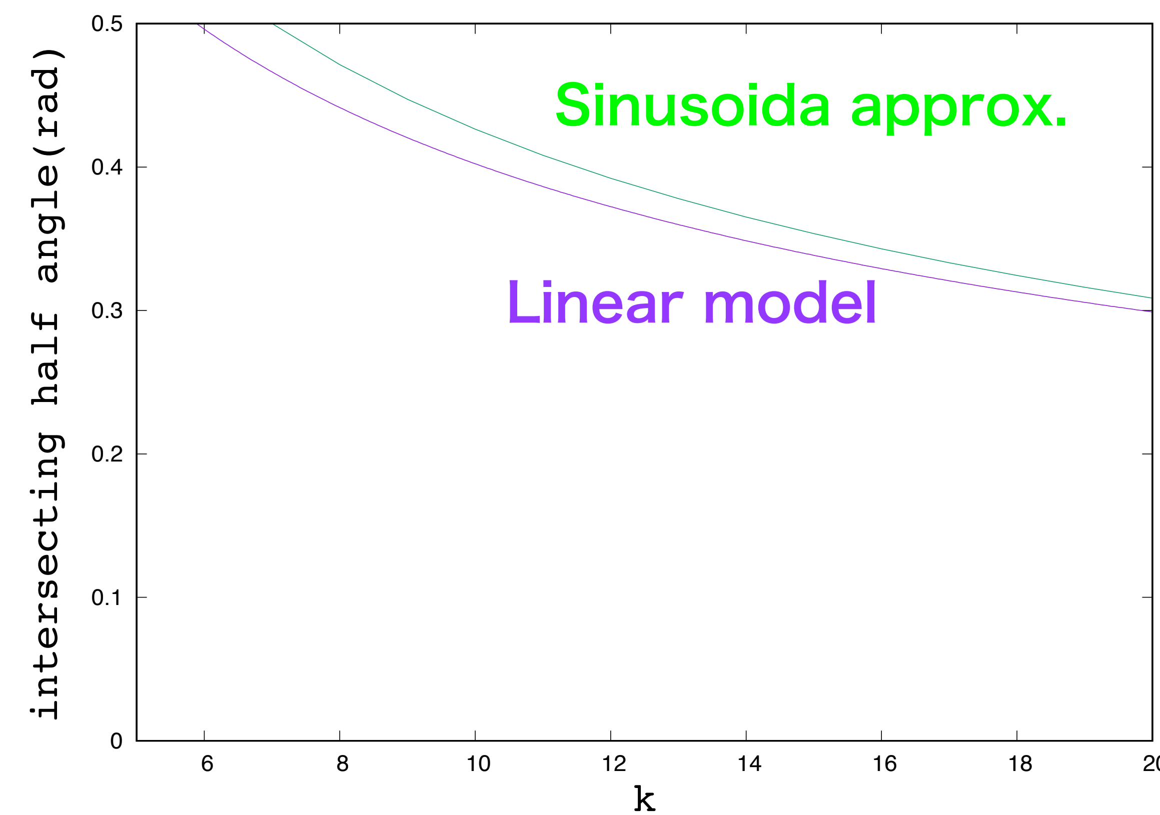


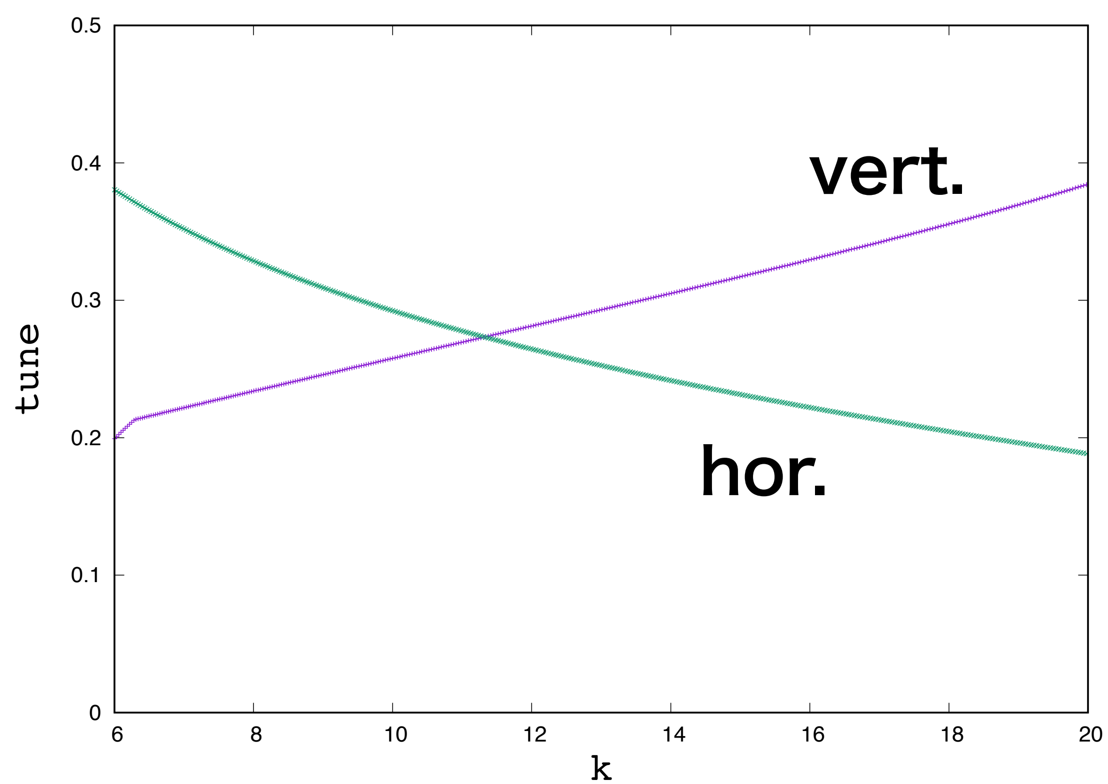
# Characteristics & Performance




stable region for number of cells(N), f/d ratio and k-value




Colliding(intersecting) angle as a function of k-value




Betatron tunes vs. k-value

Based on sinusoidal approximation(Ohkawa),a colliding angle is estimated as,

$$\psi \simeq 2\sqrt{\frac{2}{k+1}}$$

# Luminosity

- Luminosity : coasting beam

$$L = \frac{m_1\lambda_1 m_2\lambda_2\bar{\beta}c\sqrt{1-\bar{\beta}^2\sin\bar{\phi}^2}}{\tan\bar{\phi}\times h_{eff}}\times 2N_c$$

- Limitation
  - Beam-beam tune shift

$$\Delta Q_i = -\frac{Z^2}{A}\frac{\pi R\lambda r_0}{\beta^2\gamma A_{eff}}\beta_i^* \qquad \left(A_{eff} = 4\pi\sigma_y\left[\sigma_x^2+\frac{\pi R^2\phi^2}{N_c^2}\right]^{1/2}\right)$$

$$|\Delta Q_i| < 0.05 \sim 0.1(\text{for } \beta^* \simeq \frac{R}{Q}\ )$$

  - Instability (microwave)

$$\left|\frac{Z_0}{n}\right| \leq F\times\frac{|\eta|E_c}{eI_0\beta^2}$$

cf. $\beta$<1: $|Z_0/n|$~200Ω(空間電荷)

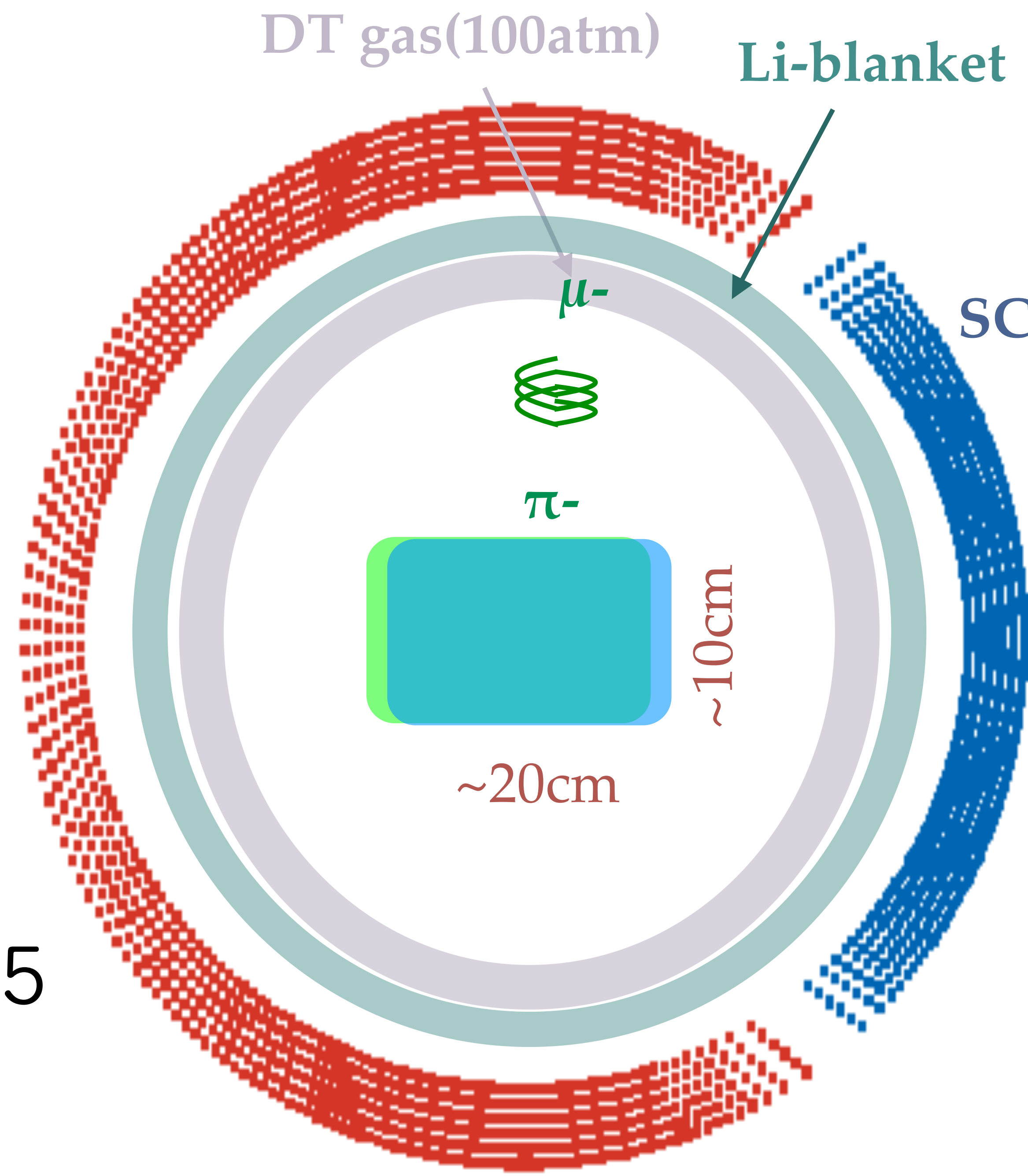
→ I<10kA : Luminosity >$10^{40}$cm$^{-2}$s$^{-1}$

# Luminosity estimation & summary

- Parameters
  - m=10(number of closed orbit)
  - Nc=20(number of FODO-cells)
    - $\sigma_{y.rms}$=0.1m
    - $\sigma_{x.rms}$=0.01m
  - beam-beam tune shift: $\Delta Q_i$=-0.05

$$L = 2.2 \times 10^{40} cm^{-2} s^{-1}$$

P(MuCF) ~1.1MW




-schematic layout of MuCF reactor-