Conceptual Design of Proton Drivers for Accelerator Driven System

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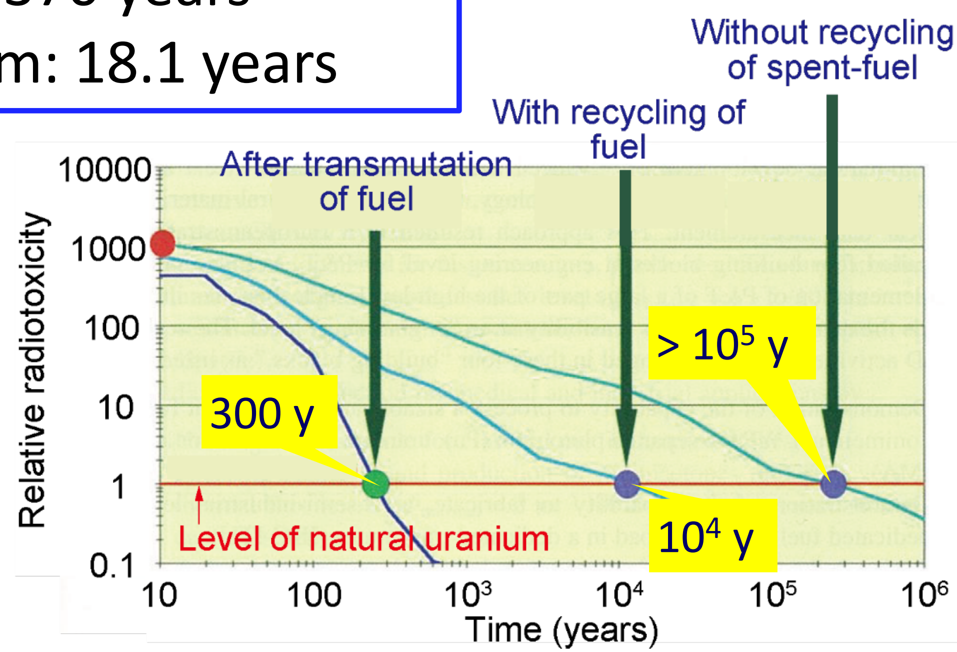
Long-term Toxicity of Nuclear Waste

1 GW reactor generates 20 t nuclear waste per year. More than $\underline{10^4 \text{ years}}$ are required to decay radiological toxicity as low as uranium.

Half-life of MA (minor actinides) in the waste
^{241}Am: 432.2 years, ^{243}Am: 7370 years
^{237}Np: 2.1×10^6 years, ^{244}Cm: 18.1 years

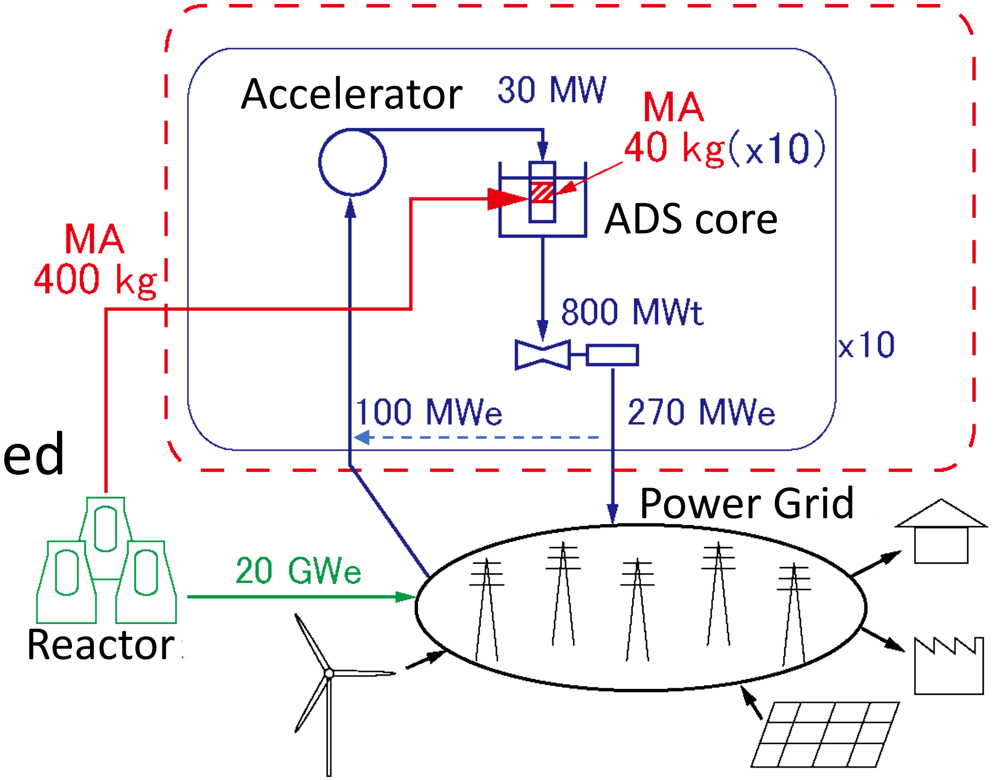
Partitioning and nuclear transmutation technology for MA can reduce the time of decay down to <u>300 years</u>.



Accelerator Driven System

Proton Beam (~ 1.5 GeV) from accelerators are injected into sub-critical core and generate neutrons to drive fission chain.

- Fuels with MA are installed into subcritical reactor cores.
- The reactor core generates 800 MW thermal power and the thermal energy is converted into electricity.
- The electric energy drive the accelerators.

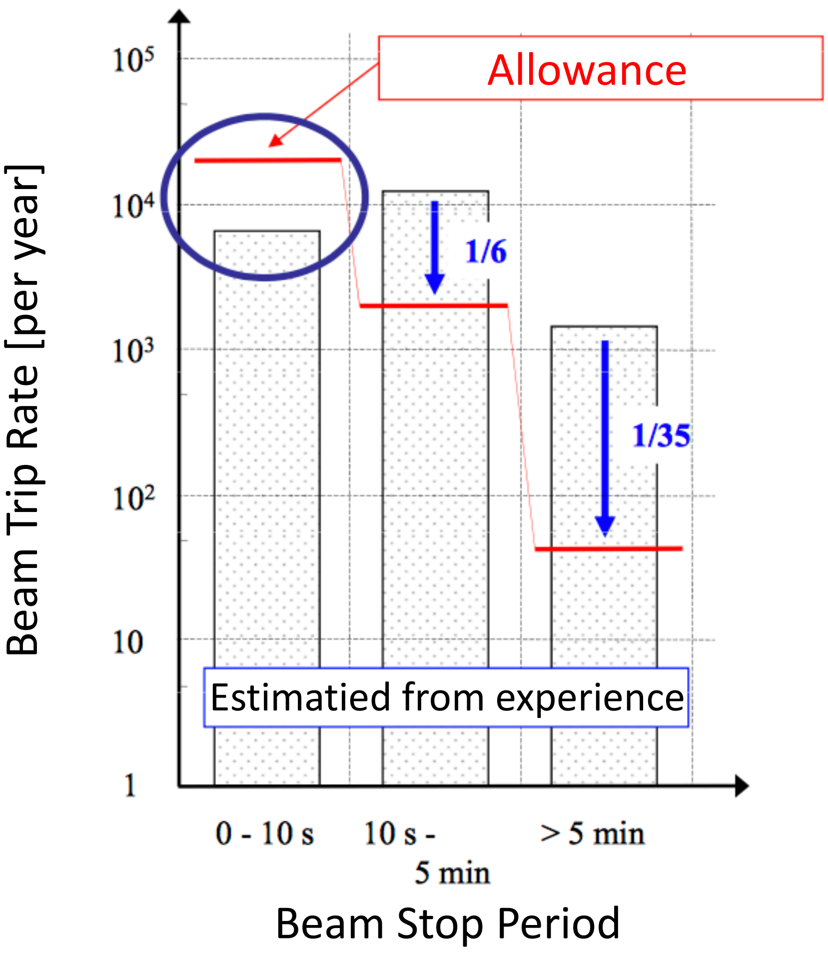


Requirement on Failure Rate

Beam trip (failure) rate is limited to mitigate heat stress in the core assembly.

Trip rates estimated from experiences on existing linear accelerator still exceed the allowable rate.

(Beam stop with the longer period occurs mainly due to failures on RF system and ion source)



Linac? Ring?, for ADS

Linac is the most promising candidate for ADS driver because of its high output beam power. However,…

The number of RF cavities and RF power sources,

Linac: ~100

Ring: ~10

Naïve estimation of the probability of the beam trip,

Linac : Ring = 10 : 1

Applying circular accelerators to ADS driver can increase reliability of ADS complex!!

What type of circular accelerator?

FFAGs and cyclotrons have advantage of high repetition rate.
(1 kHz for FFAGs, CW for cyclotrons)
And the studies on these machines for ADS have already been carrying out.

In this study, a Rapid Cycle Synchrotron (RCS) is picked up as an alternative (or back up) solutions for ADS.

Of course, the RCS is not for just back up solution for ADS,
but for a test bench of novel accelerator technologies.
(ex. AC superconducting magnet for bending magnets)

Requirement for RCS-prototype

Proton Energy: 0.1 - 1.5 GeV
Output Beam Power: 1.5 MW (1 mA average current)
Repetition Rate: 100 Hz
Power Consumption: < 4.5MW (30 % efficiency)
-> High temperature AC superconducting magnet

Occupied Area: < 50 m square
-> Compact ring with resonant extraction

Consideration of power consumption

In a conventional RCS, one of the dominant source of power consumption is Joule loss in magnet coil (~ a few MW).
Using superconductors, power loss is the coil can be critically reduced.
~ 0.2 MW due to AC loss in superconductor

Estimation of Total Power Consumption

Accelerating Cavity	2.5 MW
Loss in coil (superconductor)	0.2 MW
Core loss	0.7 MW
Others (power supply etc.)	1.1 MW
TOTAL	**4.5 MW**

Resonance Extraction

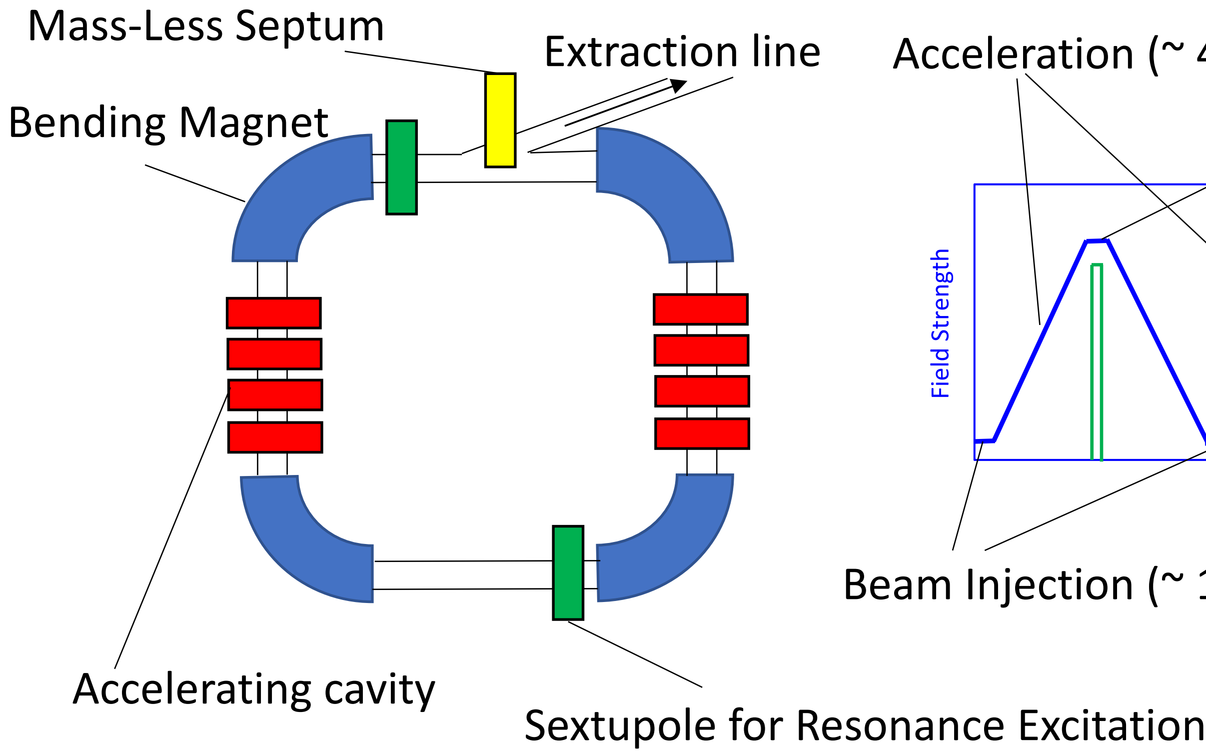
3 rd-order Driving Term:

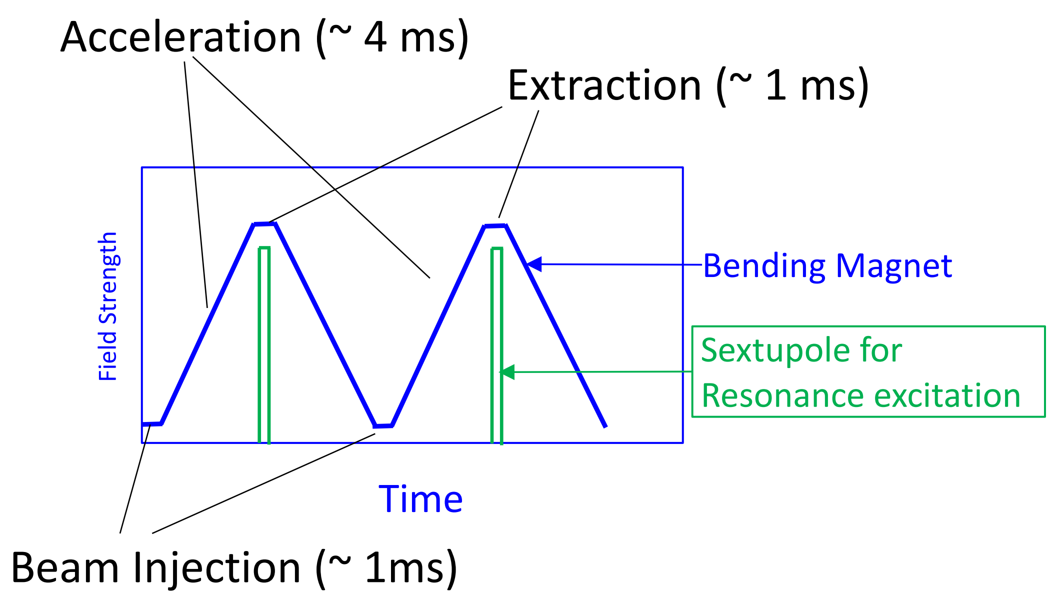
Sextupole Strength

$$\nu_x = \nu_{x,bare}\left(1 + \xi_x \frac{\Delta p}{p}\right)$$

$$G_{3,0,l} = \frac{\sqrt{2}}{24\,\pi} \oint \beta_x^{3/2}\, S(s)\, e^{i[3\chi_x(s) - (3\nu_x - l)]} ds$$

Resonance Condition: $3\nu_x = l$ (integer)





RCS Lattice consideration

1. Separated Function Lattice

2. Combined Function Lattice

<u>Basic Parameter of Lattice</u>

Symmetry: 4

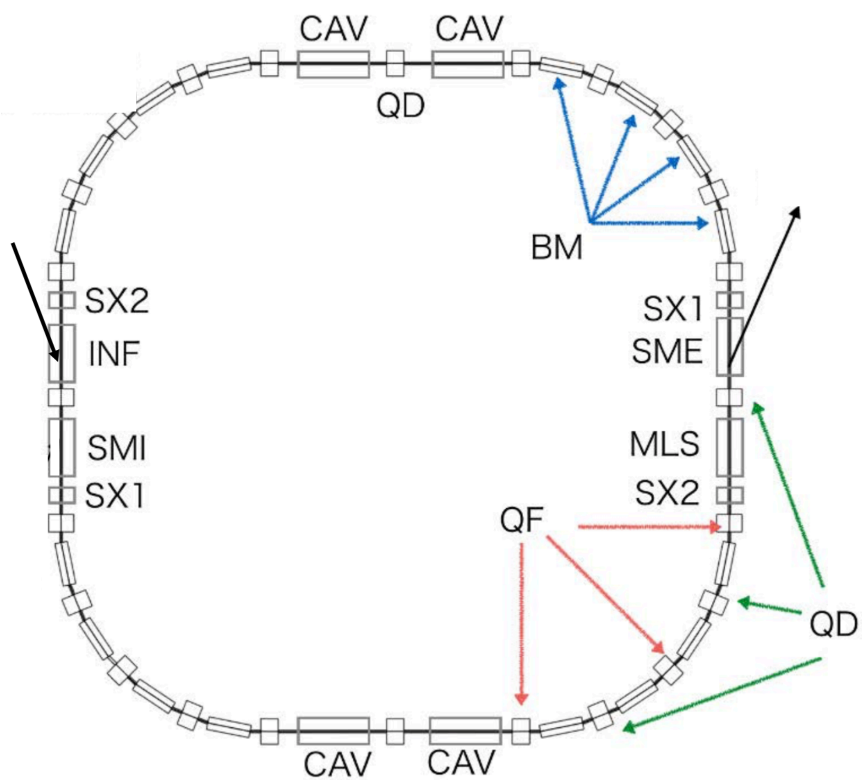
Max. magnitude of Bending Field: ~ 1.4 T (ρ = ~ 5m)

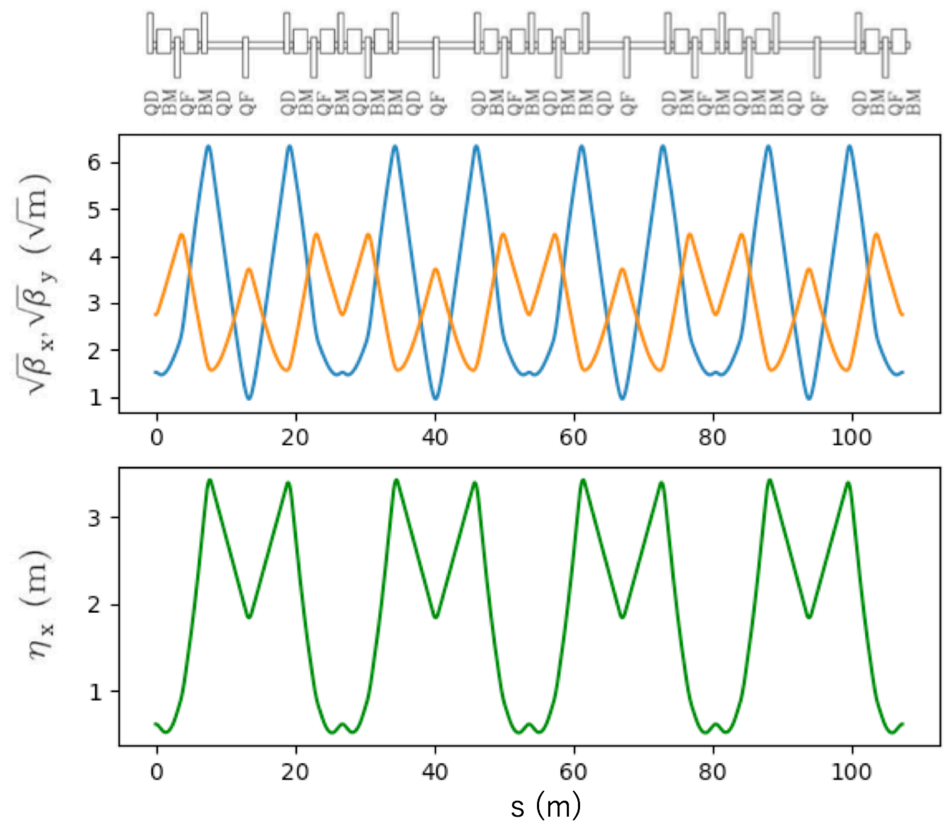
Length of long straight section: 6 m

Bare tune: $(\nu_x, \nu_y) = (3.67, 2.74)$ ← $3.67 \approx 11/3$

Momentum compaction factor: ~ 0.09

Separated-function Lattice (1): Magnet Layout

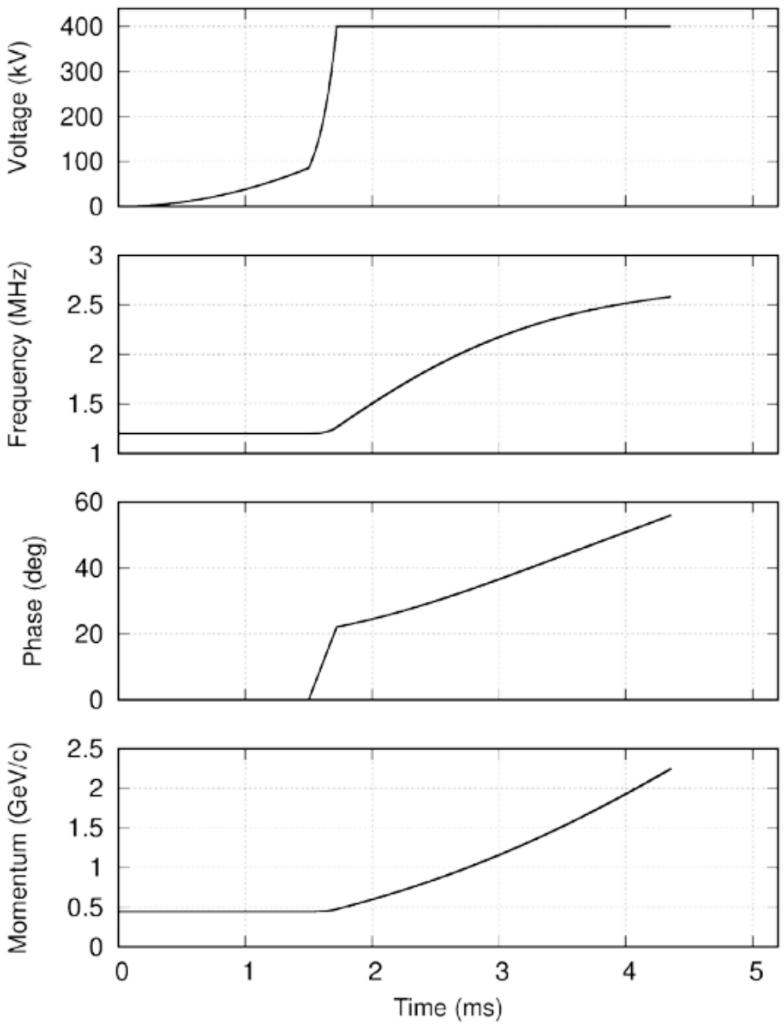


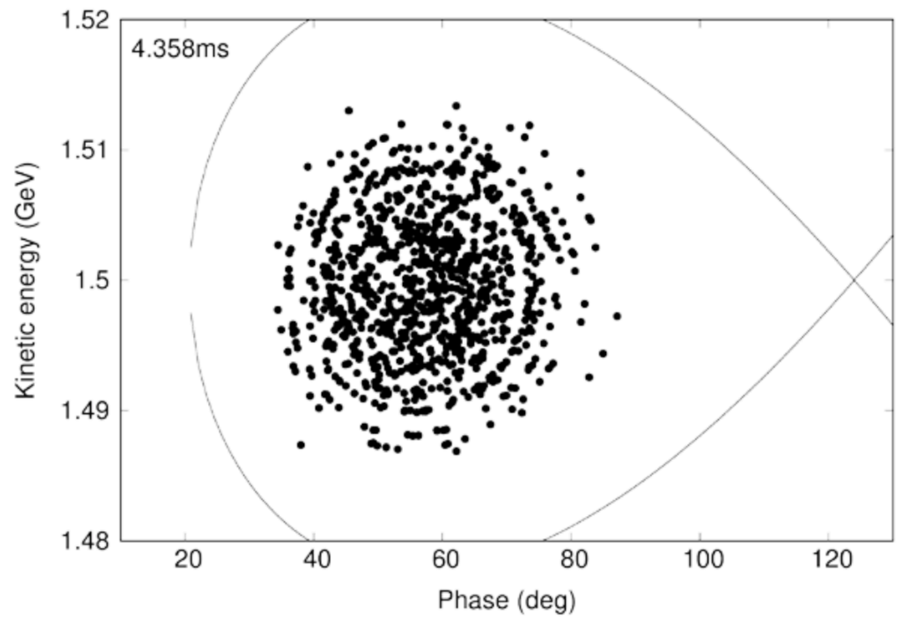


Circumference: 107.2 m

Length of BM: 2.000 m (× 16)

Separated-function Lattice (2): RF operation Pattern





Harmonic number: 1

Maximum Voltage: 400 kV/turn

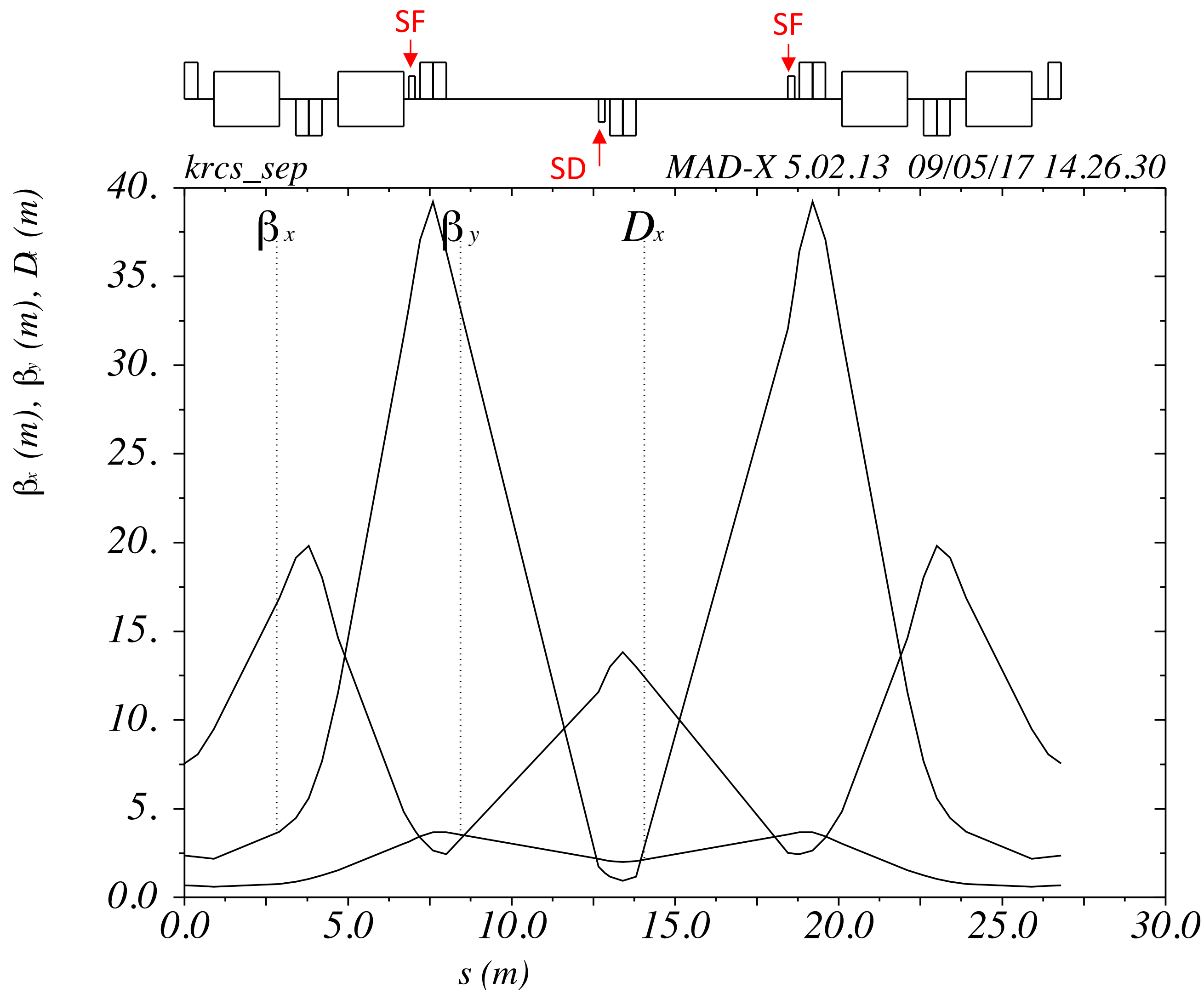
Frequency: 1.2 – 2.6 MHz

Period between inj. and acc.: 4.4 ms

Separated-function Lattice (3): Chromaticity Correction

Length of Sextupole：
200 mm

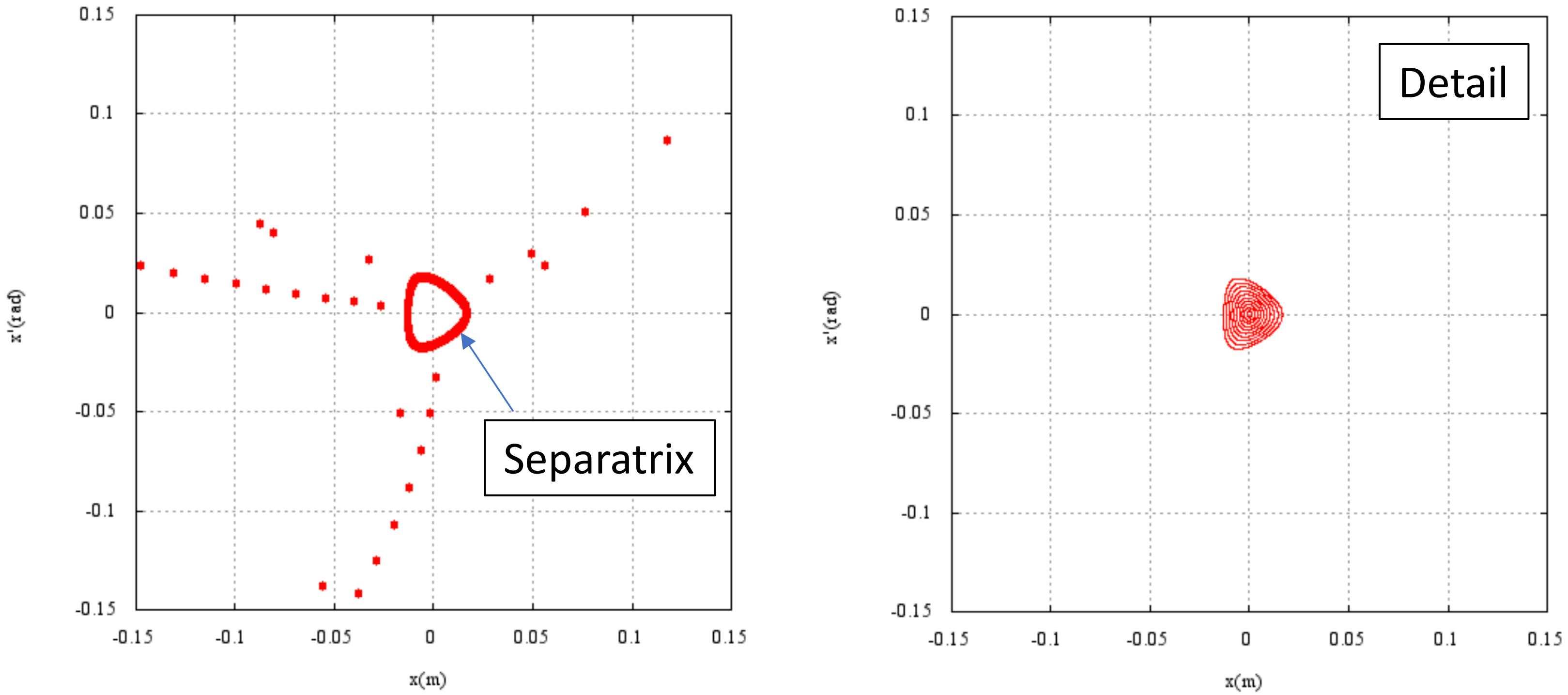
Sextupole Strength：
S_F = 2.9 [T/m^2]
S_D = 19 [T/m^2]



Bare chromaticity
$(\xi_x, \xi_y) \sim (-6, -4)$

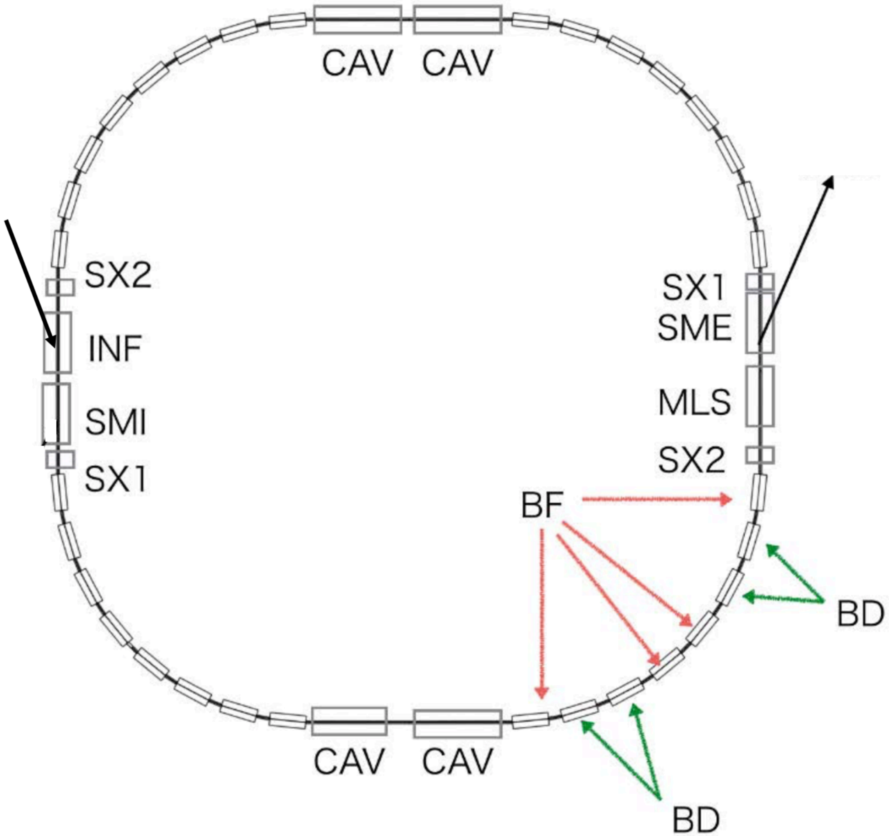
After correction
$(\xi_x, \xi_y) = (-0.63, 0)$

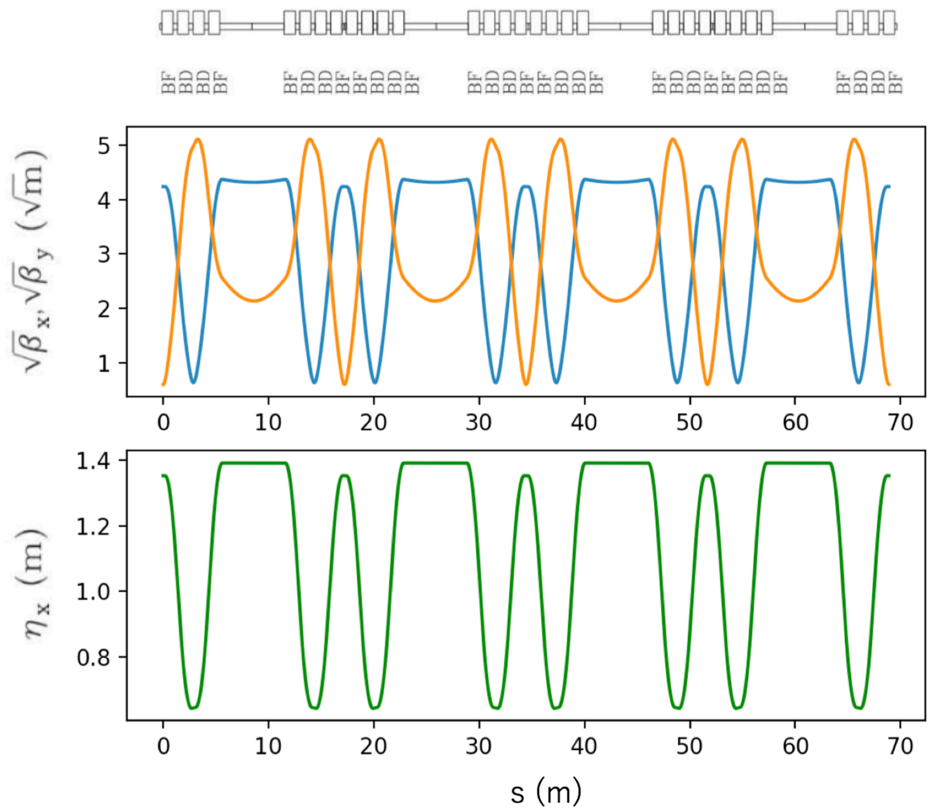
Separated-function Lattice (3): Dynamic Aperture



After chromaticity compensation, the dynamic aperture have shrink down to 4 cm.

Combined-function Lattice (1): Magnet Layout

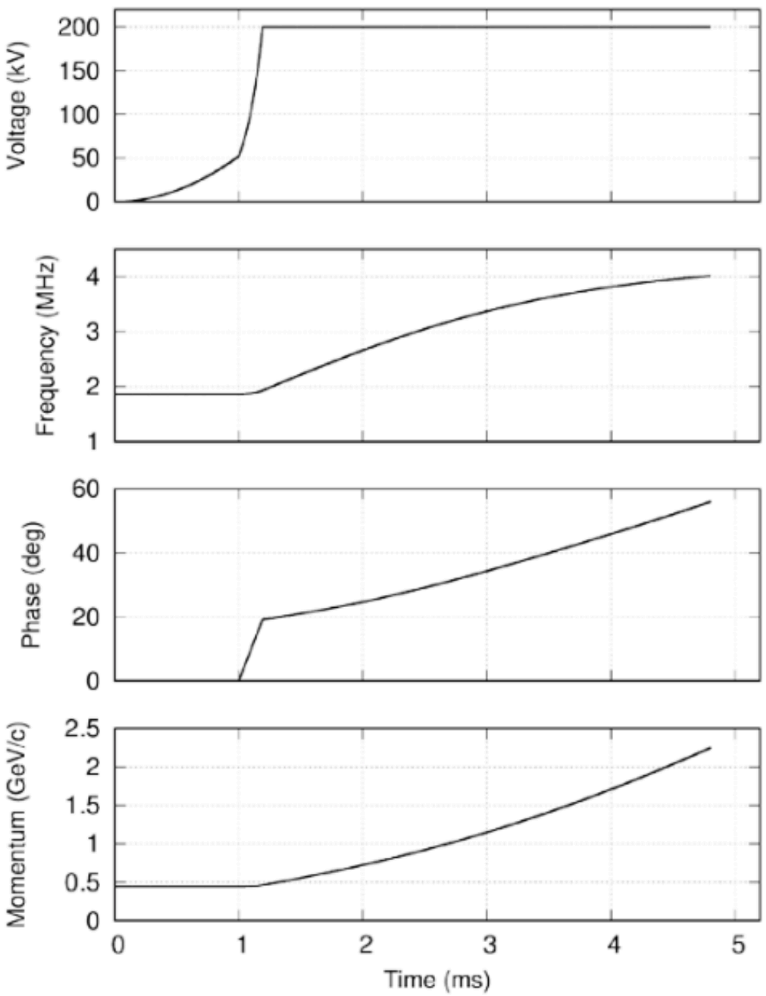


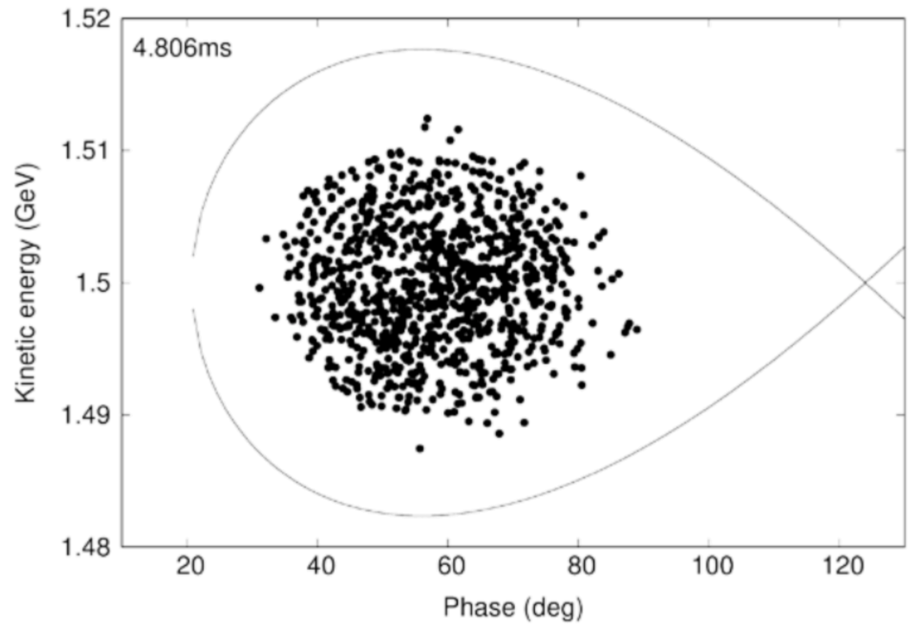


Circumference: 68.9 m

Length of BM: 1.053 m (× 32)

Combined-function Lattice (2): RF operation Pattern





Harmonic number: 1

Maximum Voltage: 200 kV/turn

Frequency: 1.8 – 4.0 MHz

Period between inj. and acc.: 4.8 ms

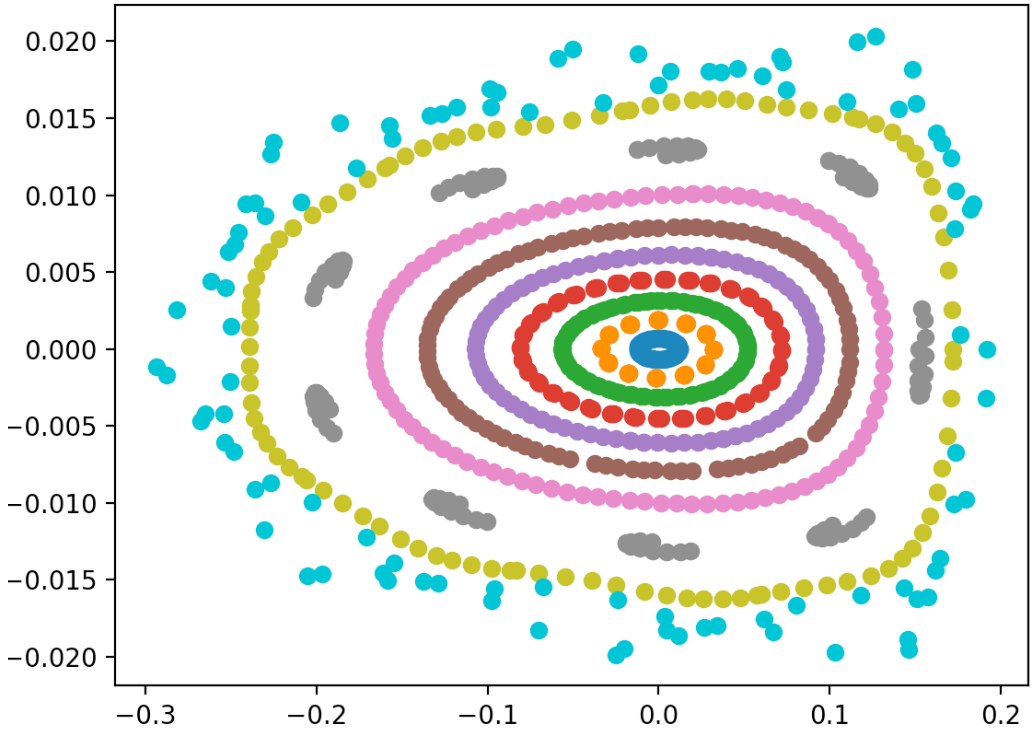
Combined-function Lattice (3)
Chromaticity Correction

Sextupole component was superposed in bending field.
BF + SF, BD + SD (<- like FFAG!!)

Sextupole Strength：
$S_F = 1.0\ [\mathrm{T/m^2}]$
$S_D = 1.8\ [\mathrm{T/m^2}]$

Bare chromaticity
$(\xi_x, \xi_y) \sim (-6, -9)$

After correction
$(\xi_x, \xi_y) = (-1.25, 0)$



<u>Large dynamic aperture can be obtained with the combined magnet.</u>

Summary of Lattice Consideration

1. Combined Function Lattice

- ◯Flexible tune correction
- ◯Long straight Section
- ▲Smaller dynamic aperture

2. Separated Function Lattice

- ◯Compact Scale Ring
- ◯Larger Dynamic Aperture
- ▲Fixed Tune

Perspective

Based on the lattice design study, 3D models of the magnets will be constructed.

Combined by the investigation results on superconducting wires, further studies are planned on,…

- Loss estimation in both coils and iron cores.
- simulations of the field ramping.
- consideration of the magnet power supply

And so on….

Conclusion

For Proton driver of Accelerator Driven System, Rapid Cycle Synchrotrons are investigated. In order to reduce the power consumption, magnets with high temperature superconducting coil will be applied.

As the basic design, lattice with both separated and combined function magnets were studied. Based on the results, more detailed studies will be carried out.