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"New Horizons of Partitioning and Transmutation Technologies with Accelerator System"

Linear accelerator for nuclear transmutation of long-lived fission products

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本研究は、総合科学技術・イノベーション会議が主導する革新的研究開発推進プログラム（ImPACT）の一環として実施したものです。

Working group at ImPACT Program

- ImPACT Fujita Program: Fujita, Kawashima
- RIKEN : Sakurai, Okuno, Kamigaito
- Kyoto univ. : Mori
- Univ. of Tokyo: Aoki
- Osaka univ. : Fukuda
- Emeritus: Mizumoto
- MHI : Sen'nyu, et al.
- Melco : Miyashita, Hattori et al.
- Hitachi : Takeuchi, Wakuta et al.
- Toshiba : Matsuda, Sato, Sako, Ohsaki, et al.
- SHI : Aoki, Tsutsui, et al.

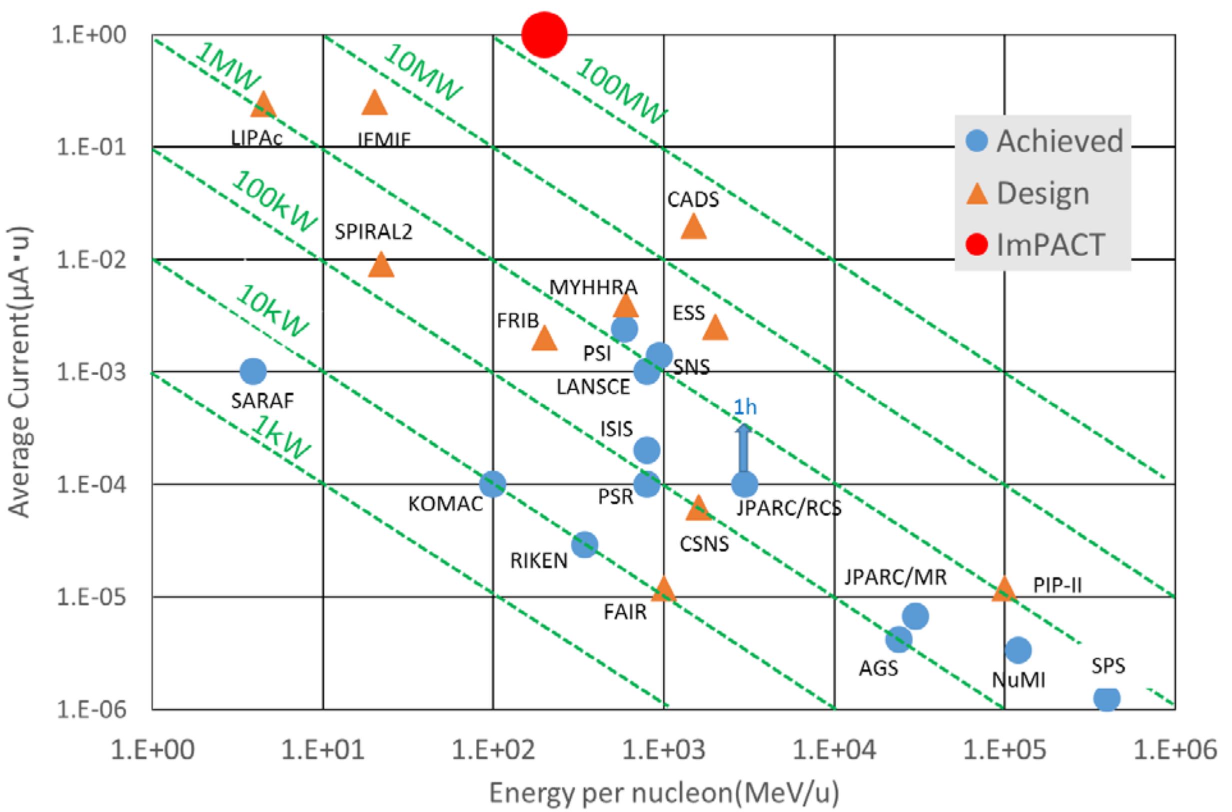
Contents

- (Introduction to ImPACT Fujita Program)
- Required specification of accelerators for nuclear transmutation of LLFP
- Issues to be solved for realization of the accelerators
- 1A deuteron linear accelerator (ImPACT2017)
  - Low beta section
  - Medium and high beta section
- Summary and outlook

Accelerator for transmutation of LLFP

Requirements

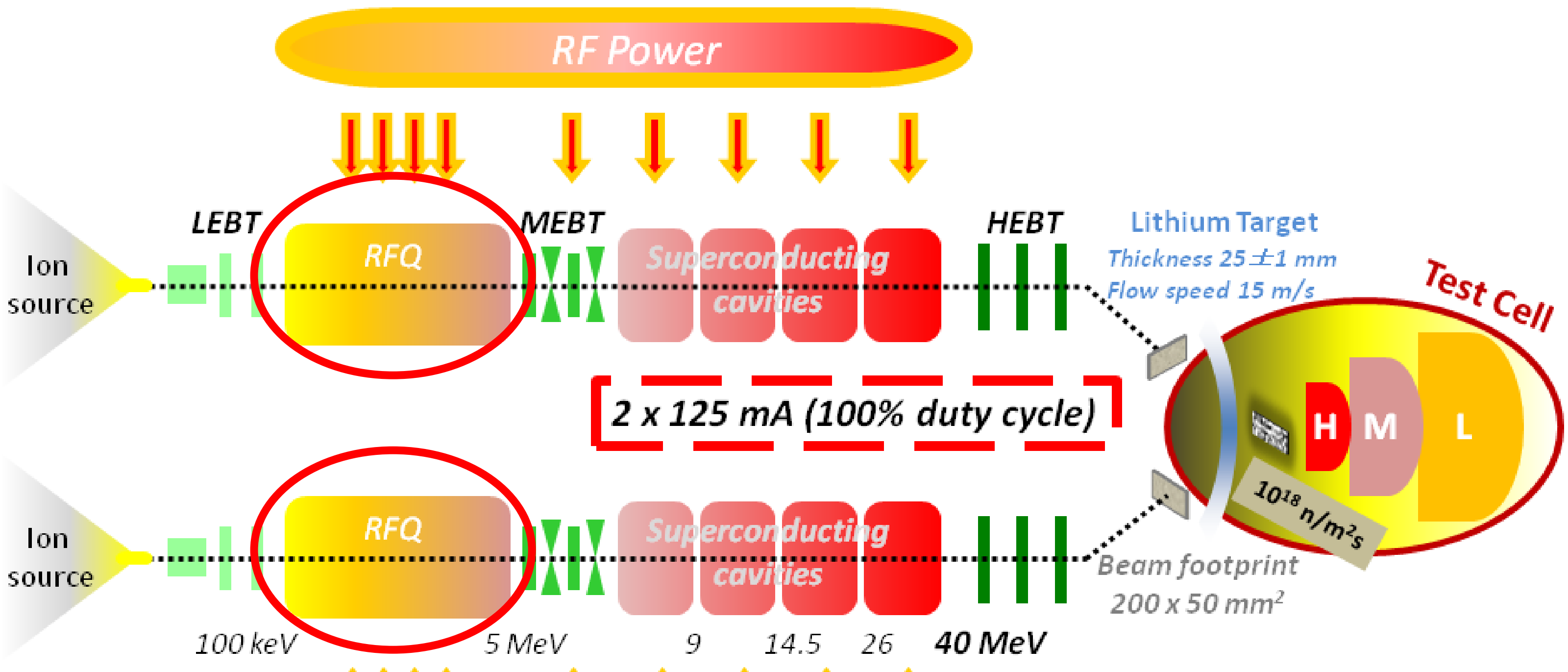
- Particle : Deuteron（including heavier elements than hydrogen)
- Energy : 40-200 MeV/u
- Current : 1A
- Beam Power : 80MW-200MW x 2 (~100 MW class)



Structure of 10 MW accelerator

IFMIF accelerator

This scheme is based on RFQ.



Available testing volume and dpa

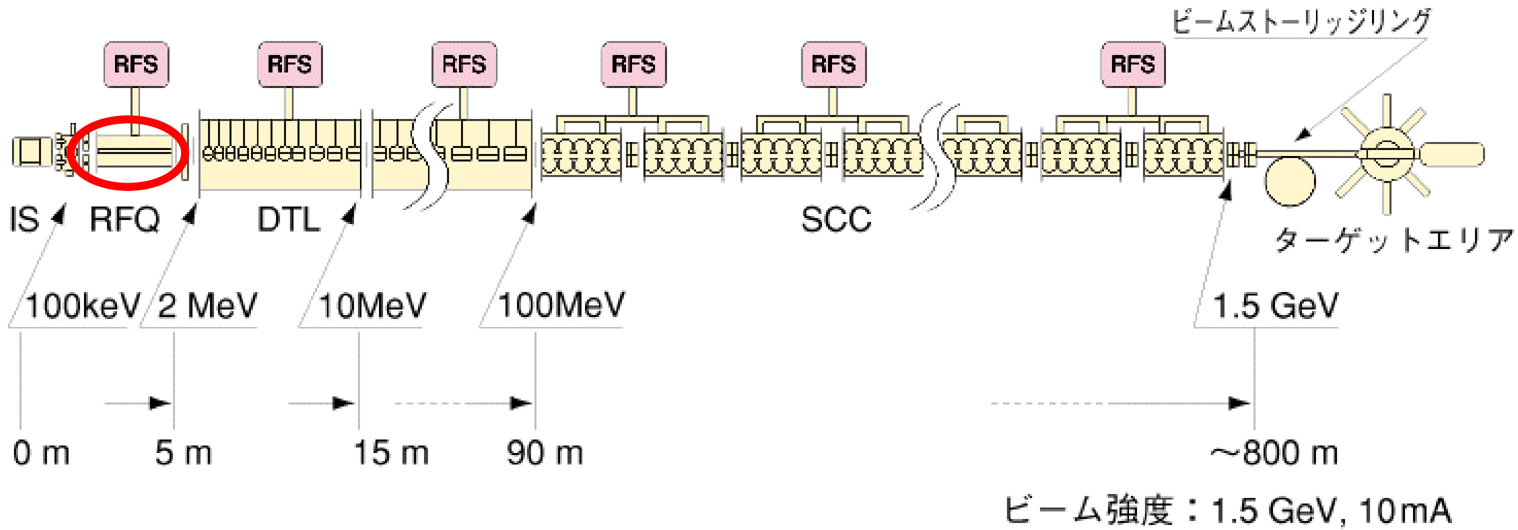
High >20 dpa/y in 0.5 liters

Medium >1 dpa/y in 6 liters

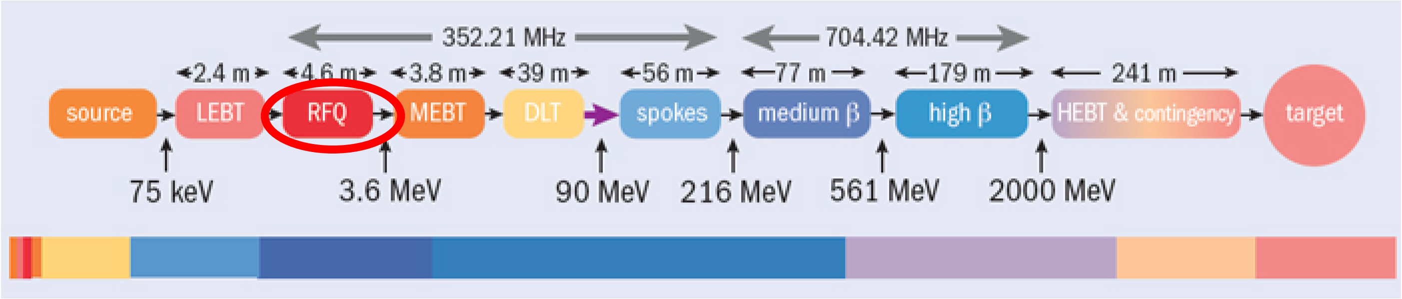
Low <1 dpa/y in 8 liters

Structure of 10MW accelerator

Modern high power proton accelerator: RFQ-based scheme



ADSの一例(Accelerator Driven System)



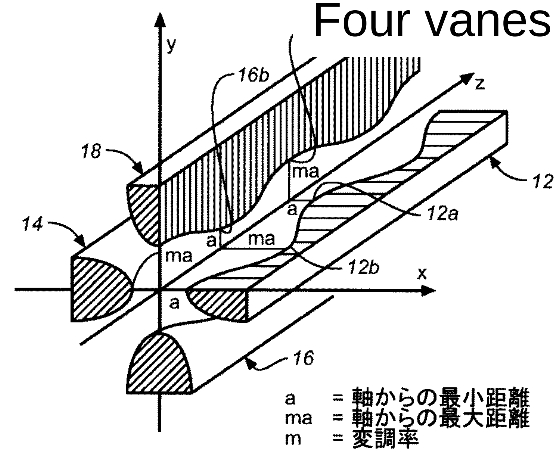
ESS (European Spallation Neutron Source)

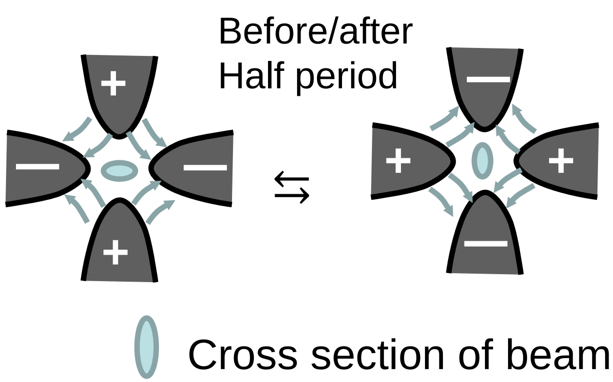
RFQ linac (No.1)

History：The principle of RFQ was invented in 1970's by Russian researchers and demonstrated at LANL. The appearance of the RFQ changed the design concept of the high power proton linac.

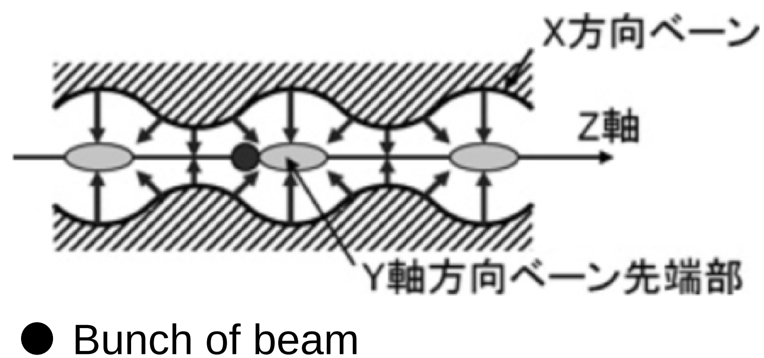
- Electric fields generated by the four vanes with longitudinal modulation can give the beam acceleration and transversal focusing simultaneously.

Four vanes structure





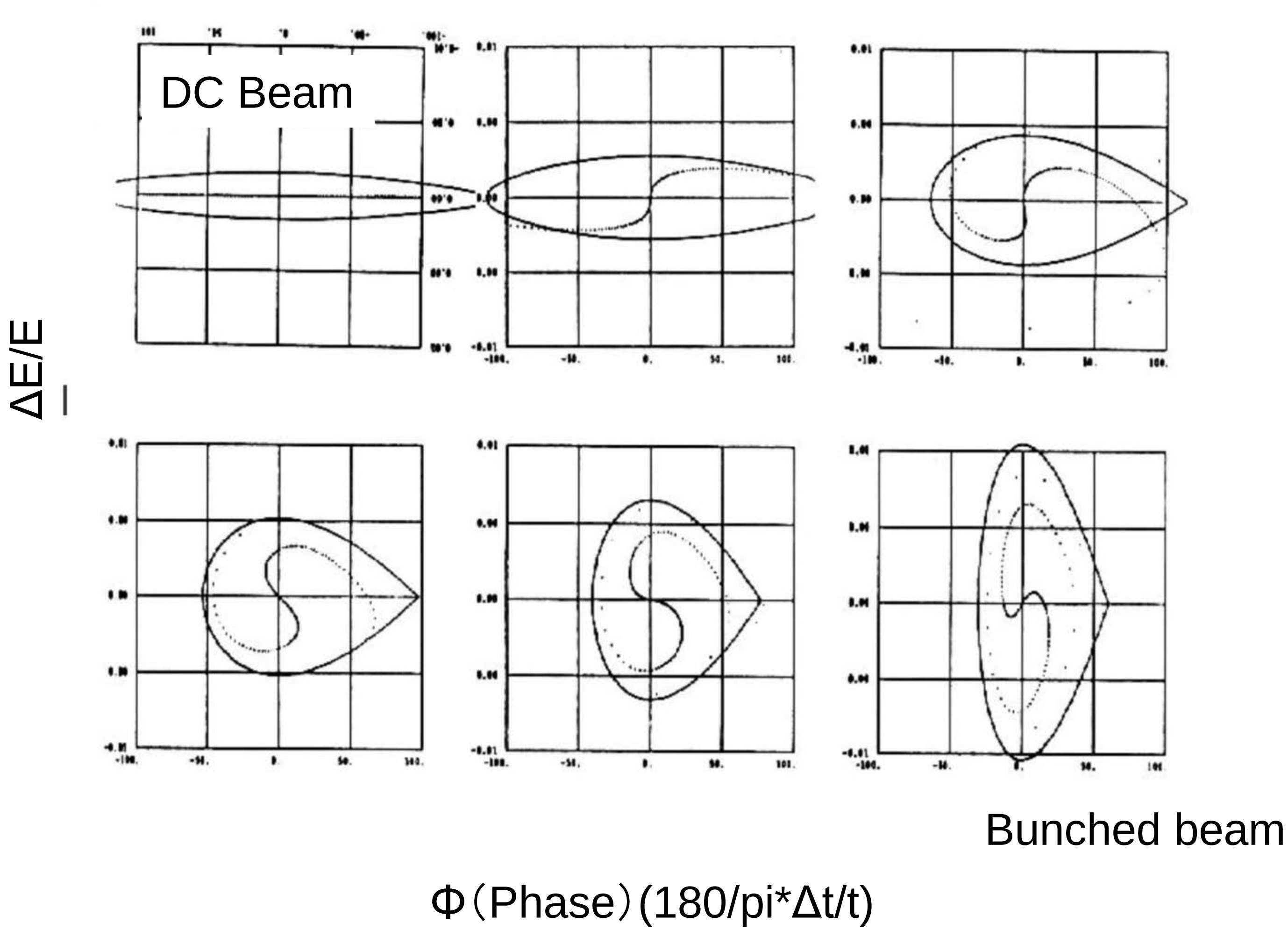
Transversal focusing



Beam acceleration

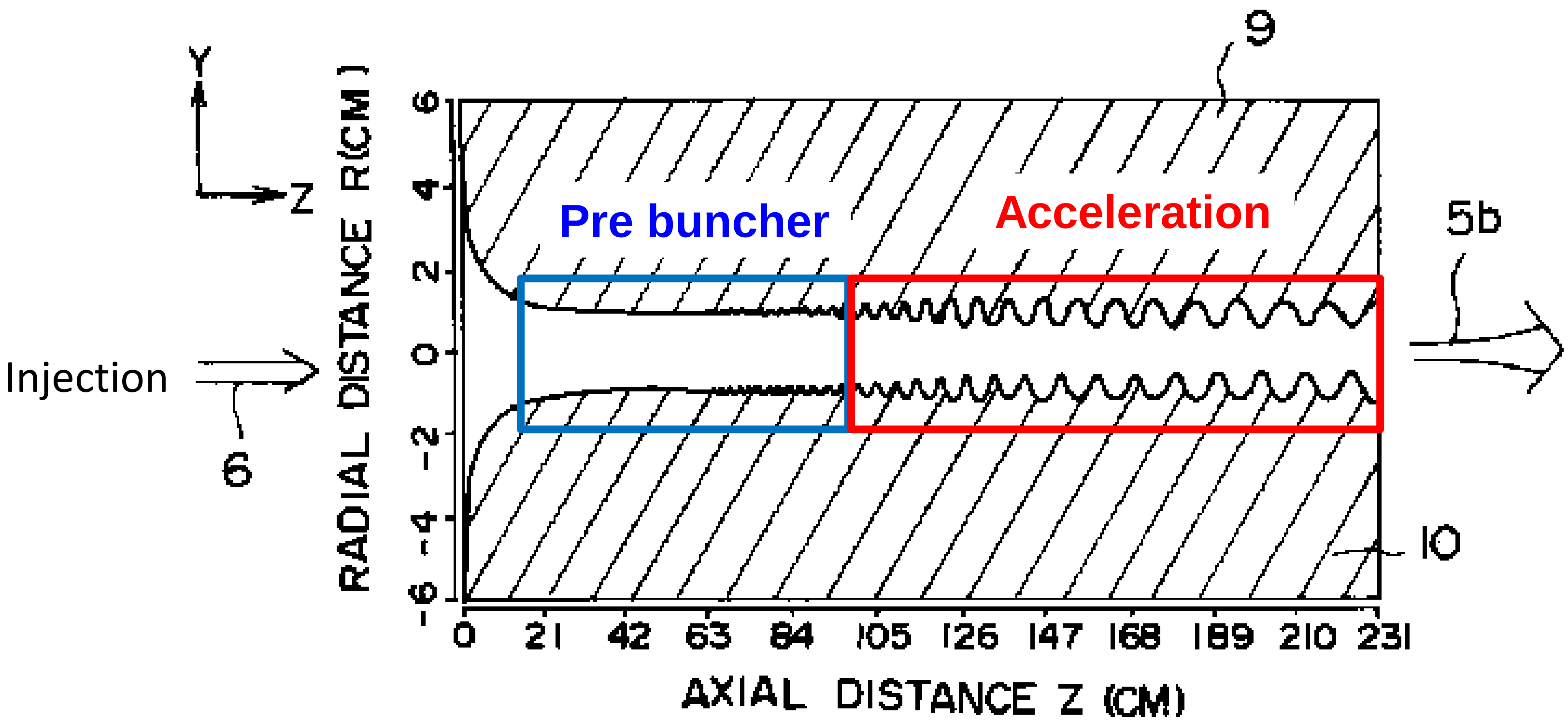
RFQ Linac (No. 2)

Another important function of RFQ:
Make beam bunch from DC beam by adiabatic rf capture



RFQ linac (No. 3)

従来のＲＦＱ電極の断面図（垂直面）（図５）



Summary of function of RFQ

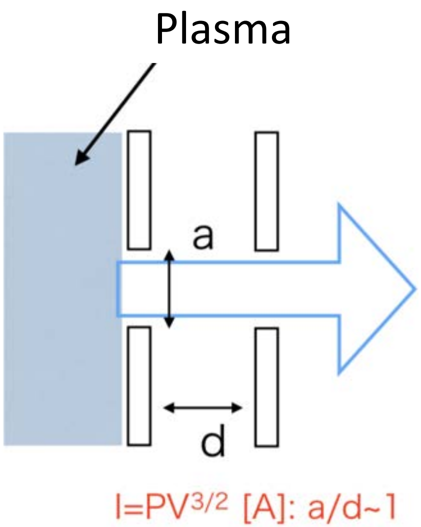
1. transversal focusing

2. acceleration

3. bunching of DC beam

Technical issue: beam bore

- Maximum current of deuteron ion from a single hole with good quality
  - $I = PV^{1.5} \quad (a \sim d,\ P = 2.5 \times 10^{-8} \frac{Z}{M})$
  - *I* depends only on extraction voltage.
  - Deuteron (Z/M=1/2) at V = 30kV
    - $I = 92\ mA$
    - More than 10 holes are necessary to get total current of more than 1 A
- About 30 holes are necessary, taking characteristics of plasma, deuteron ratio etc.. into account
  - Collection of 30 holes in diameter of 1cm make a beam of 10cm in diameter.



- **Acceptance of the succeeding accelerators should be larger than 10 cm.**

Acceptance of rfq is as small as 1cmΦ. Space charge forces are too much when the beam is focused on circle of 1cmΦ.

Technical issue: number of coupler

Beam power：100MW class

→Number of coupler：more than several x 100

(Assuming 1MW per coupler)

Coupler crisis

IFMIF RFQ

ImPACT needs more than 8 times of those in the case of IFMIF RFQ

More than 64 couplers!

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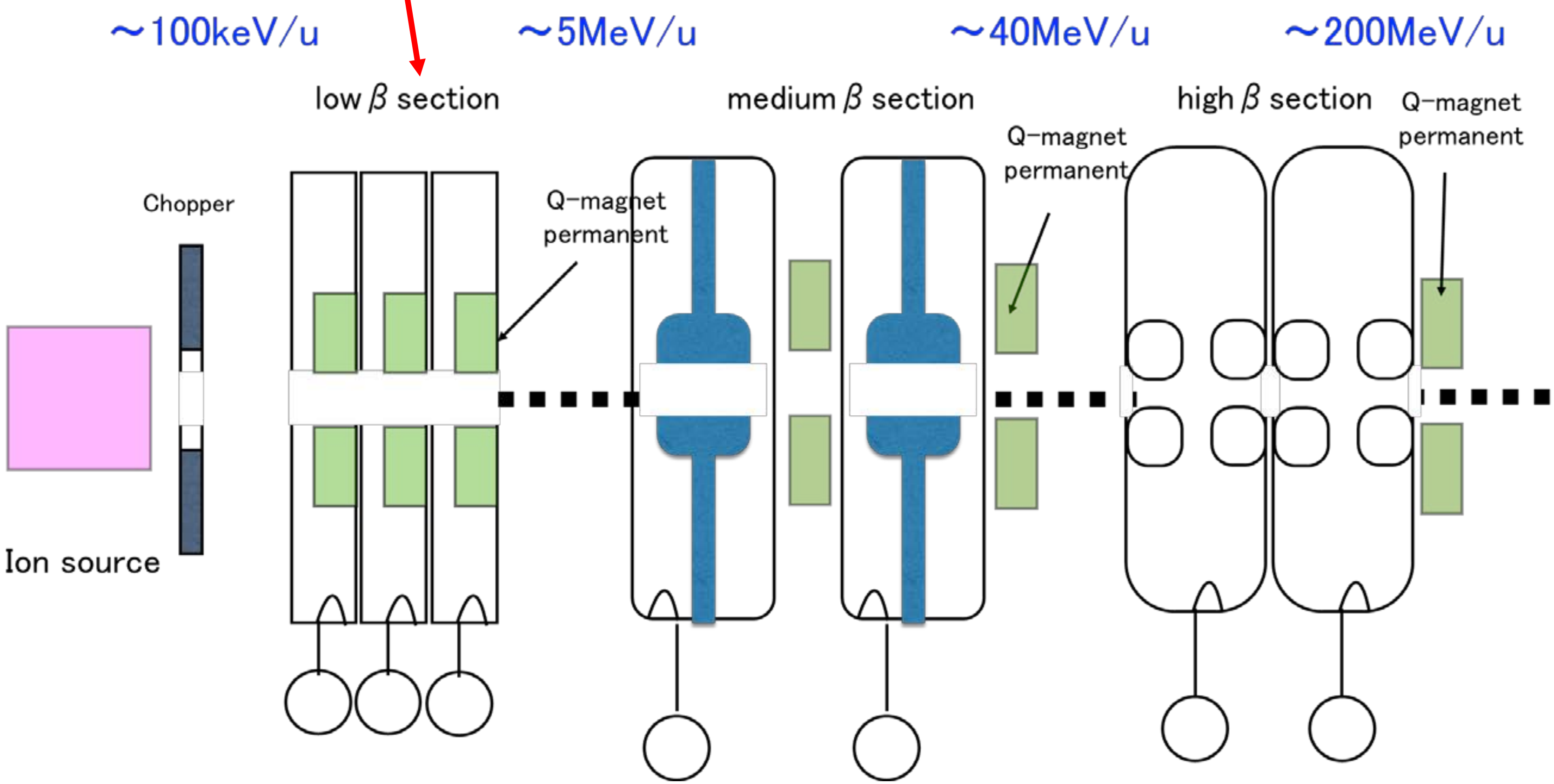
ImPACT2017 (Single cell linac with magnetic focusing)

The low beta section consists of single cell rf cavities with solenoids. It works like RFQ but can accept large bore beams.

Single cell cavity
- Reduction of number of rf coupler per cavity.
- easier to give the high power beam the rf power
- Rf phase can be freely selected for beam tuning.



f~25MHz, V=0.3MV (1gap)

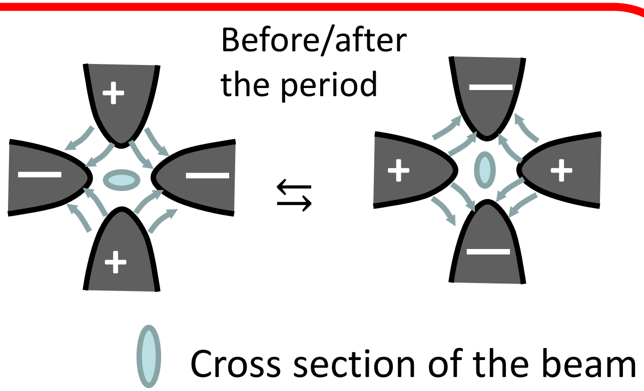
f~50MHz, V=2.5MV (2gap)

f~100MHz, V=2.5MV (1gap)

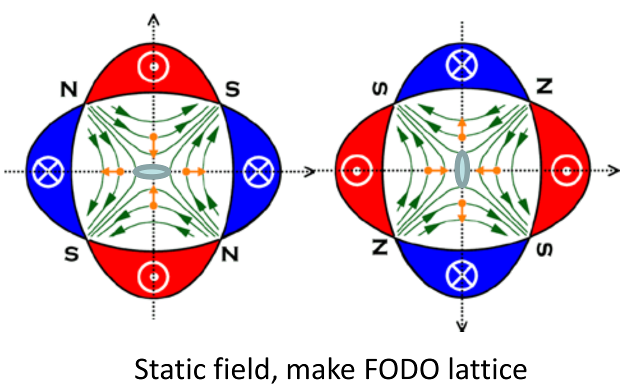
Magnetic focusing with large bore

Magnetic focusing: it can accept large bore beam.

	RFQ(1cm)IFMIF	RFQ（10cm）	Rf with Q（10cm）
Bore radias	**1cm**	**10cm**	**10cm**
Required V	80kV	800kV	300kV
E field	25MV/m	25MV/m	---
Discharge limit	**1.8 Ekp**	**beyond limit**	**No limit**
Rf loss	1MW	100MW	<10MW
Gap distance	βλ/2	βλ/2	No restriction
Adiabatic rf capture	○	○	○



Electric focusing

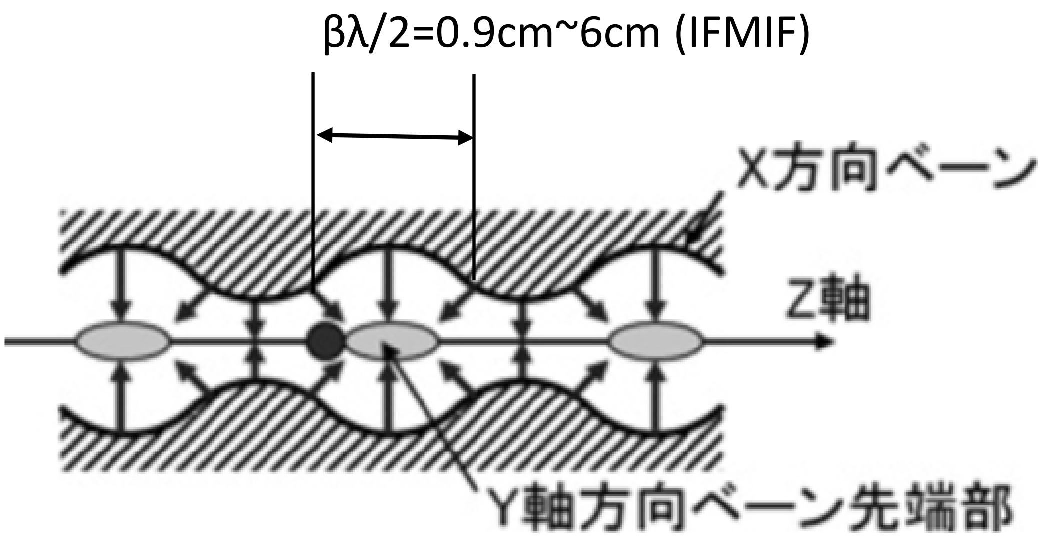


Magnetic focusing

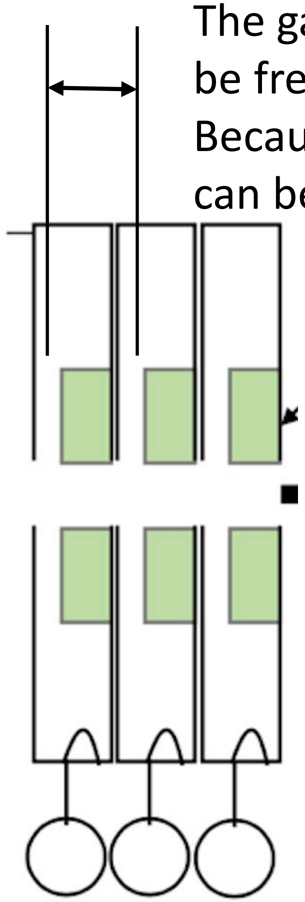
Rf gap distance in linacs

RFQ

β=velocity/c (the light velocity)
λ＝c / f (frequency)
βλ＝distance which particle runs in one period.



Single cell linac



The gap distance can be freely chosen. (~30cm)
Because phase of each cavity can be independently tuned.

Low frequency (25MHz~)
rf system is required to keep transit time factor around 1.

Length of Linac

E_d (MeV/u)	I_b(A)	lowβ #	Medium β #	High β #	total
40	>1	10MV ~20m	70MV ~60m	-----	~80m
100	>1	10MV ~20m	70MV ~60m	120MV ~60m	~140m
200	>1	10MV ~20m	70MV ~60m	320MV ~160m	~240m

 # assuming 4 couplers/cavity (1.6 MW/cavity)

Low β section

Medium-β and high-β section

Summary

- Required specifications
  - Deuteron ＞1A、100MW, 40MeV/u~200MeV/u
  - Large bore for high current but limit of bore of RFQ
  - Number of the coupler
- ImPACT2017 model
  - No RFQ, Single cell cavity with magnetic focusing.
  - Low-beta section（beam dynamics including linear space charge forces, cavity with a superconducting solenoid.)
  - Medium-beta and High-beta section (beam dynamics, design study of the cavity)
  - We have found no essential problem so far.
- Future issues

Future issues

- Issues for Accelerator physics
  - Ion sources
    - Beam current limitation due to space charge force (Langmuir-Child limit)
    - Deuteron beam（Imax ~90mA/1hole）
  - Beam dynamics
    - Dynamics in the longitudinal direction（at the entrance of low-β and medium-β）
    - Resonance
    - Beam halo
    - Rf acceleration
    - Beam loading
    - instability

標的：Target

- Issues for Engineering
  - RF source
    - Low frequency rf sources　～several 10MHz、high power　(beam power：～100MW)
    - Multi coupler：digital control
  - Energy saving（Improvement of efficiency of rf amp、permanent magnet.)
  - Radiation damage