

Lead talk: High-Intensity Linacs

“Proposal of a 1-ampere deuteron single-cell linac”

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How should we design a next-generation
highest-intensity linac?

Contents

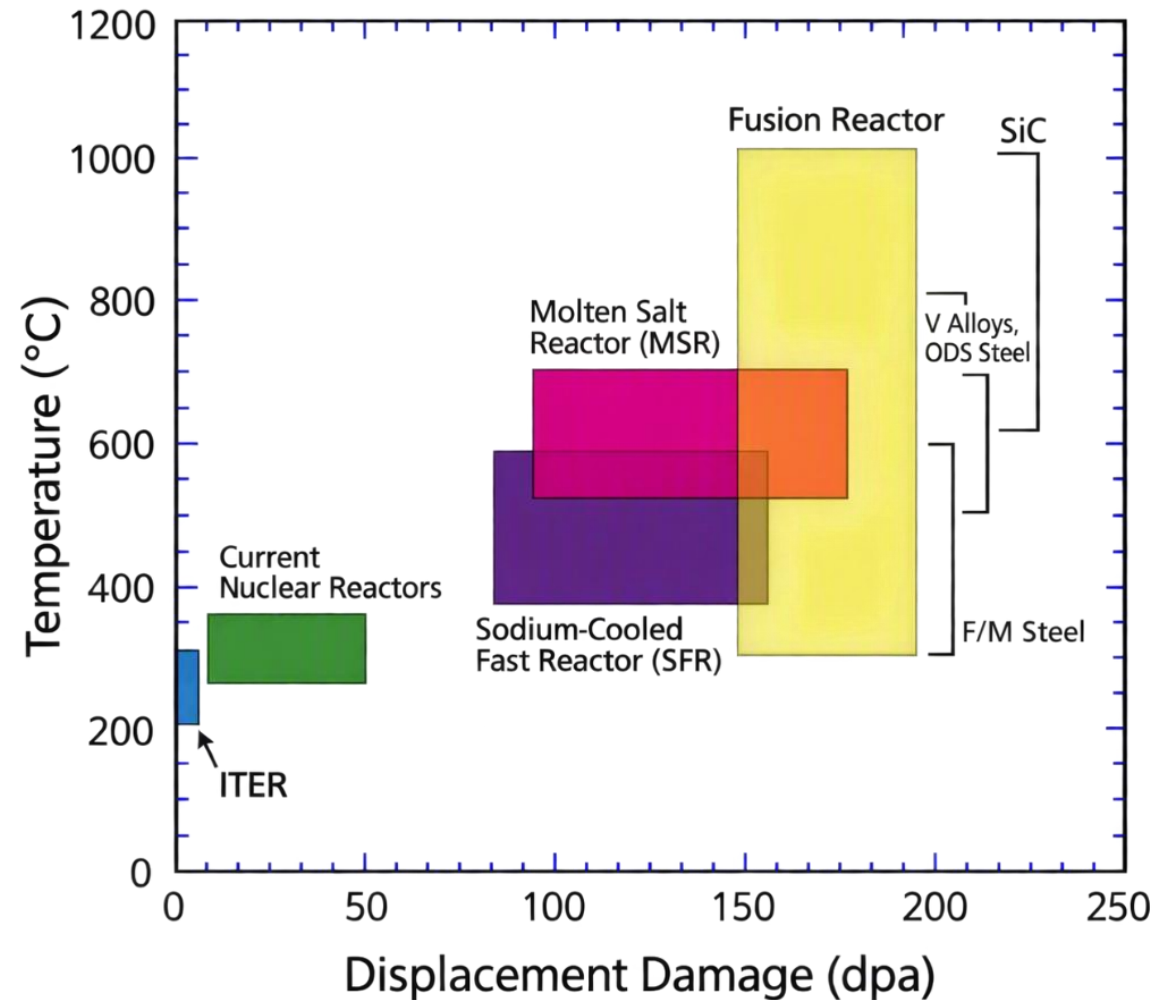


- **Introduction**
 - Fusion-science motivation
 - Requirement to the accelerator
- **Proposal of 1-ampere class single cell linac**
 - no RFQ (can accelerate large size beam)
 - Concept of 1-ampere single cell linac
- **Low beta section**
 - Ion source + LEBT
 - Tune depression(compared with EES and DONES)
 - TTF problem (Low frequency rf system and broad)
 - Bunching of of 1A beam in 3D simulation
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- **Summary**

Motivation: Fusion Materials Science



- Fusion reactors require materials that survive extreme neutron damage
- High-flux irradiation → requires **high-power deuteron beams**
- **DONES (125 mA) is currently under construction and will be capable of irradiating materials up to 50 dpa/fpy; however, it is intended only for the irradiation testing of a very limited amount of materials for Euro-DEMO.**
- **1-A deuteron beam → pathway to next-generation fusion materials testing**



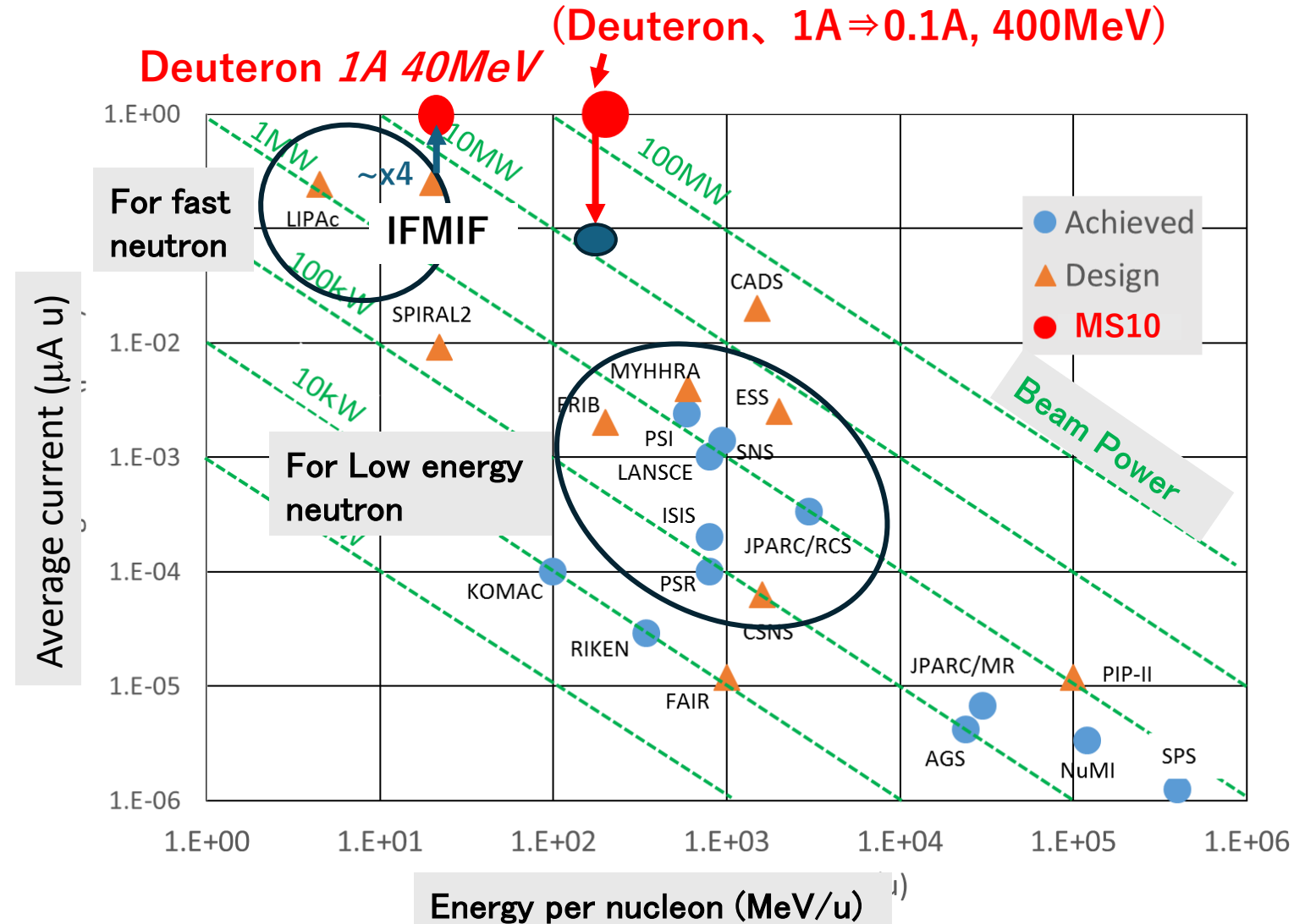
Comparison of Accelerator Performance Worldwide



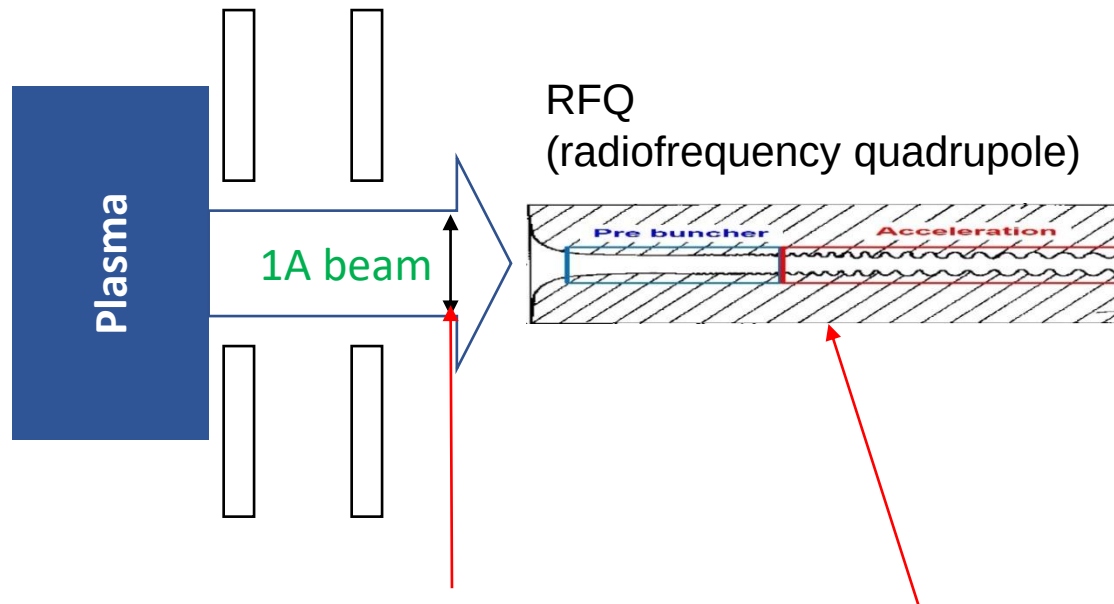
ITER NBI
Deuteron 1MeV 20A

Requirements to the accelerator

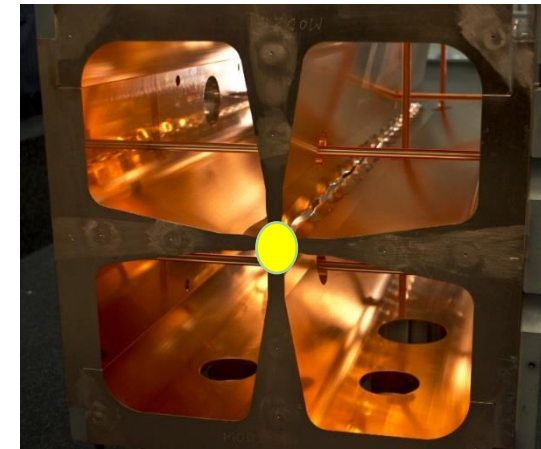
- Particle : Deuteron
- Output Energy : 40 MeV
- Current : 1A
- Beam Power : 40MW



RFQ (radio-frequency quadrupole) linacs are widely used as front-end accelerators in the high-intensity, high-energy proton (deuteron) linacs. It works as a buncher of DC beam from ion source, electrical transverse focusing elements, accelerator.



Size of 1A beam $> 10\text{cm}\phi \gg 1\text{cm}$: typical acceptance of RFQ



● Cross sectional view of RFQ

The area which beam can go through.

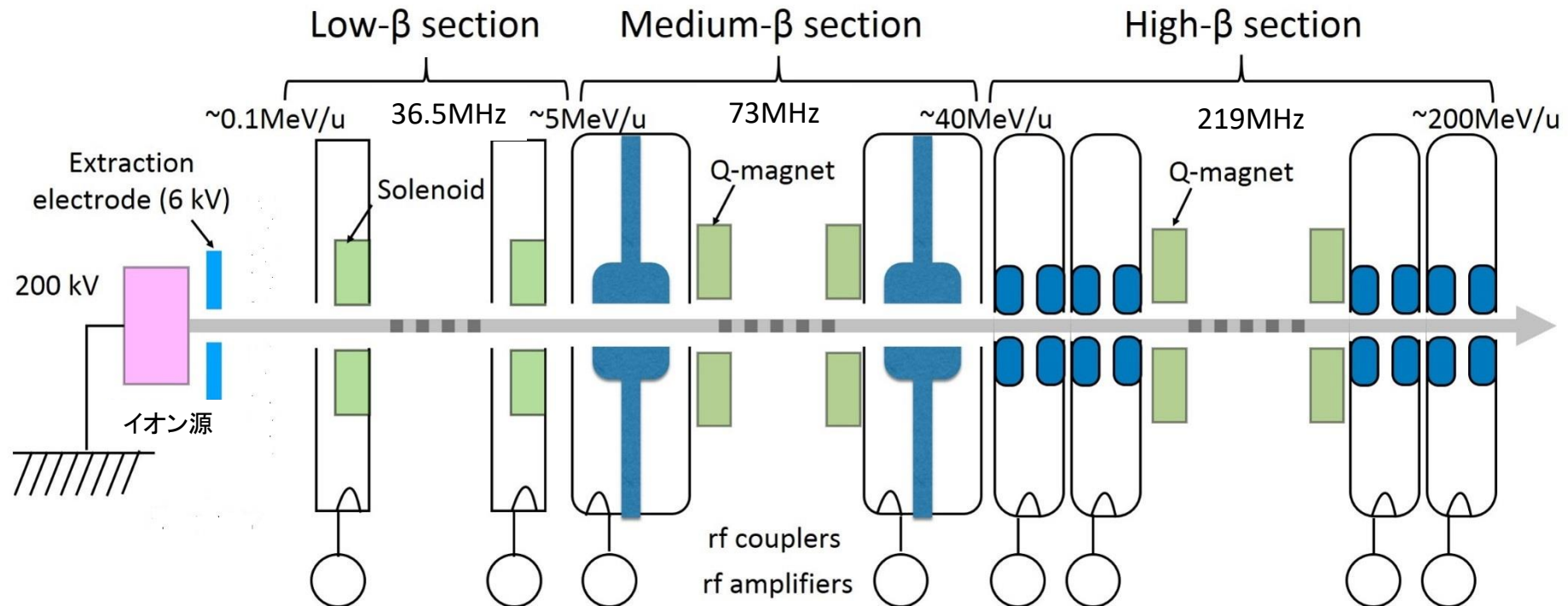
We can't use RFQ !!

Concept of Single-Cell Linac for 1A beam

Single-cell cavities + magnetic focusing elements (without RFQ)

Merits:

- 1: It can accept large beams because it uses magnet focusing elements free from discharge.
- 2: Low current density owing to the large beam size mitigates space charge force.
- 3: Voltage and phase of each cell can be independently selected to compensate for the longitudinal space charge effects, and also to implement an efficient bunching function for a



Key Technical Challenges and Solutions for a 1-A Deuteron Linac



Challenge 1: Development of a Low-Energy Front End Enabling RF Acceleration of Large-Aperture

Challenge 2: Achieving the Required Beam Loss Level (10^{-8})

Approach: Develop a new beam halo analysis methodology to meet the beam loss requirement corresponding to 1 W/m.

Limit the beam power

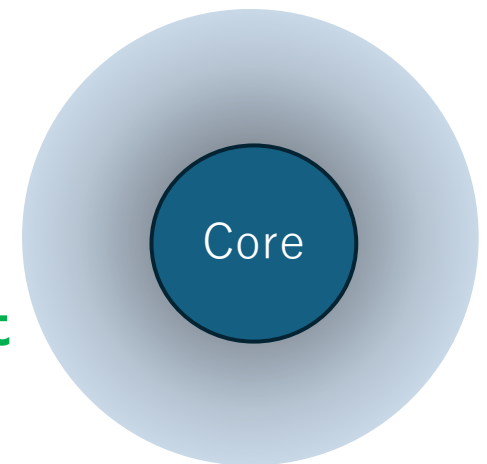
Challenge 3: Demonstration of a 1-A Deuteron Beam from the Ion source

Challenge 4: Scaling Superconducting RF Cavities to Large Aperture and High Power

Challenge 5: Advancing the Target Concept to the Conceptual Design Stage

Challenge 6: Improving Electrical efficiency of the accelerator

These challenges define the core of the MS10 accelerator R&D project

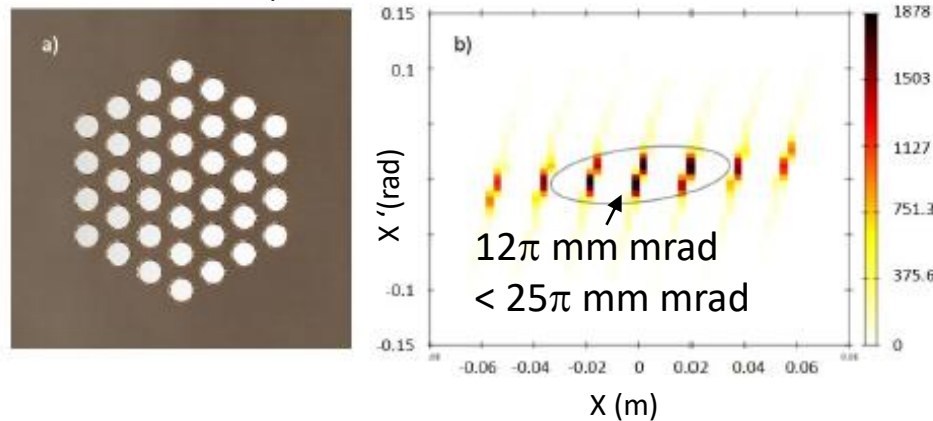


Ion source + LEBT (low energy beam transport)

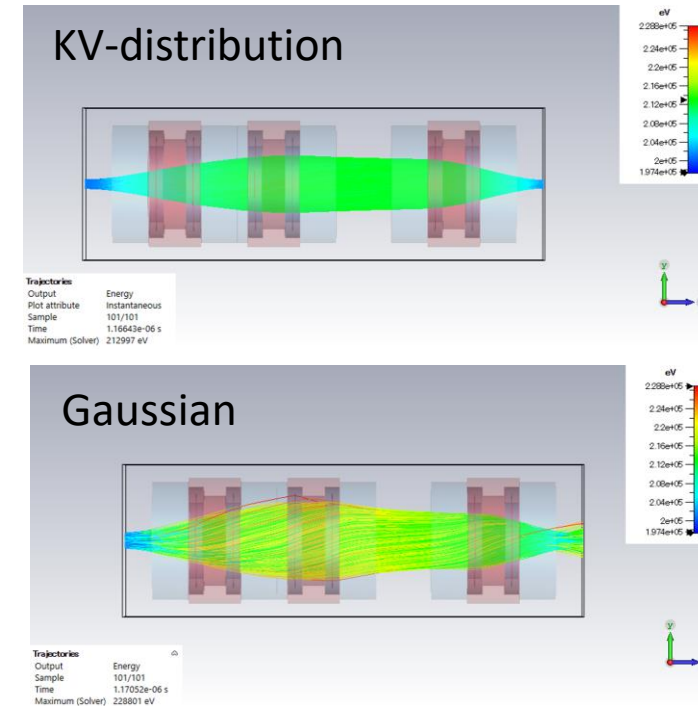
Ion source: A cusp-field confinement type ion source used for NBI (Neutral beam injector) in Tokamak fusion reactors. Extraction from the multi hole is inevitable.

Multi-holes for beam extraction (14mm ϕ x 37)

Emittance of extracted beam

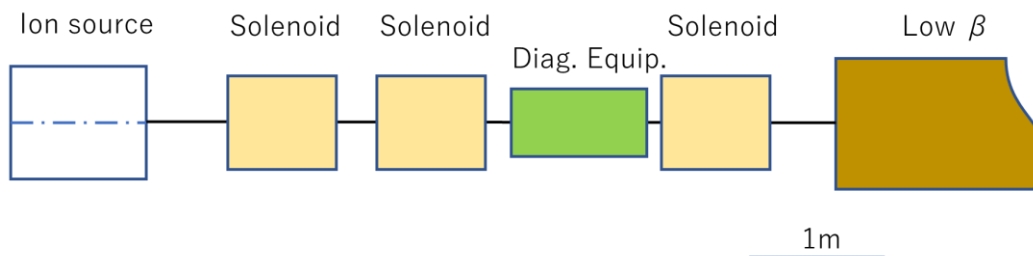


Beam envelope in the LEBT (no neutralization is assumed.)



This multiple beamlet cause mismatch resulting in Beam halo?

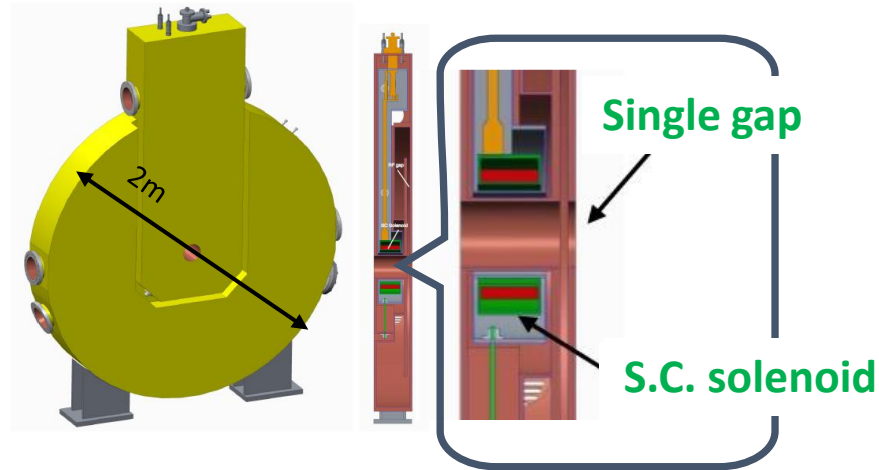
Plan view of LEBTp



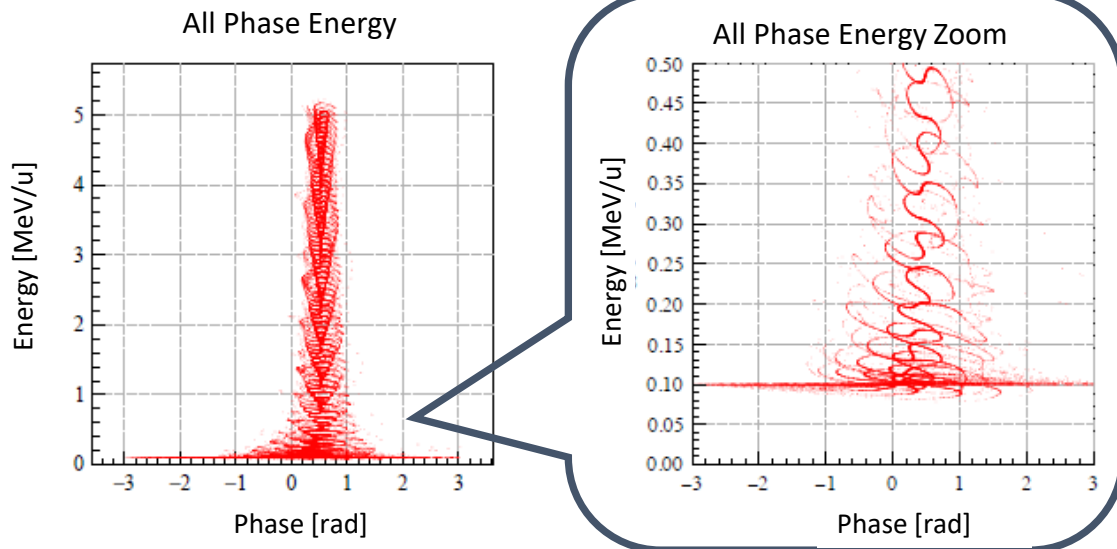
studying on beam halo with various initial conditions

Low β section (adiabatic rf capture)

> 90 cells (Single gap with S.C. solenoid)



Longitudinal Beam behavior: Adiabatic rf capture
(DC $\rightarrow$ bunched beam)



Key issues

(1) Strong space charge forces

Make Tune depression small, placing the beam near resonance conditions.

(2) Transit time factor reduction

Large apertures broaden the energy distribution across the RF gap. Low RF frequency is required to maintain adequate TTF.

(3) Adiabatic capture

RF frequency, gap voltage, and synchronous phase must be carefully chosen.

Tune depression at injection energy

Tune depressions of 1A deuteron linac are large compare with those another high power linac because of large aperture.

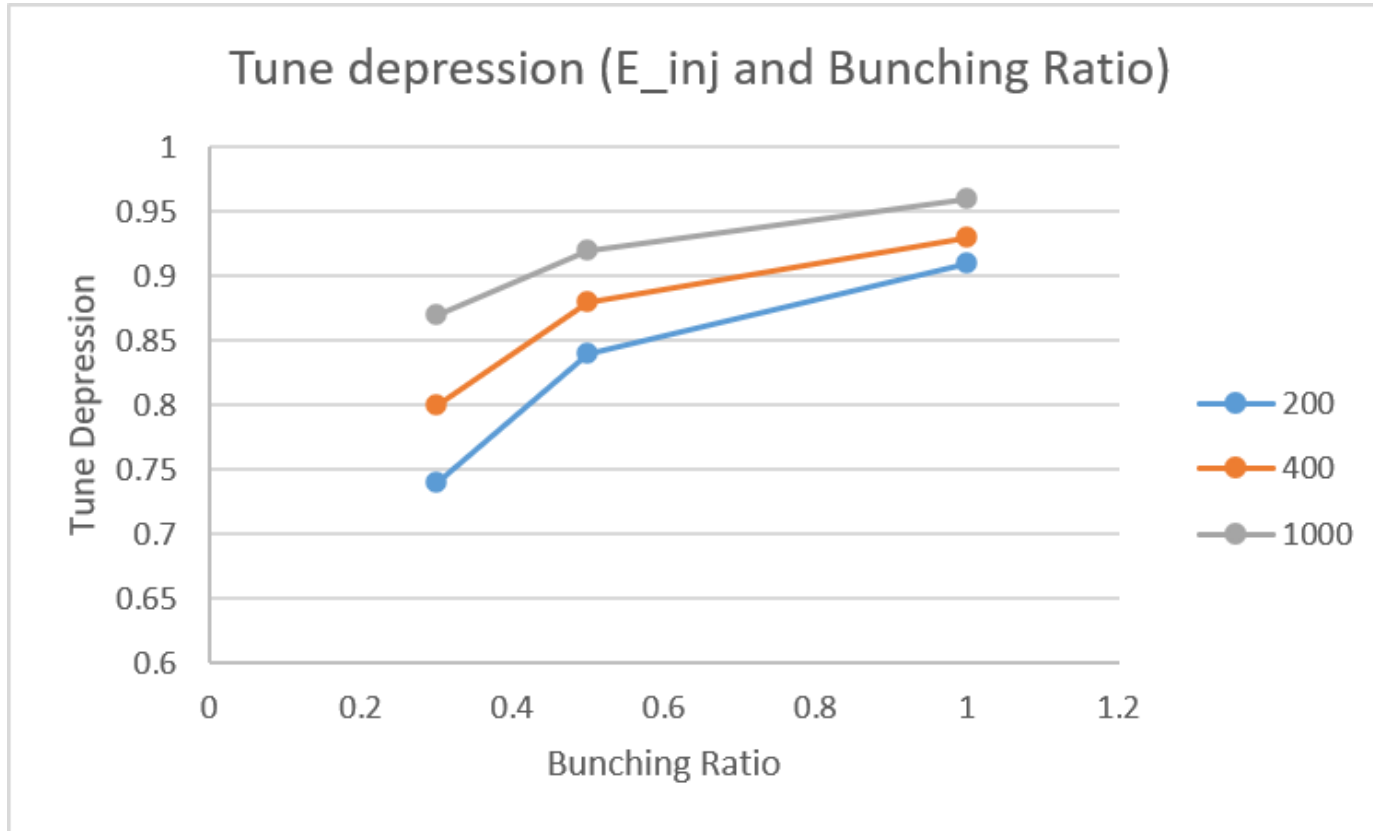
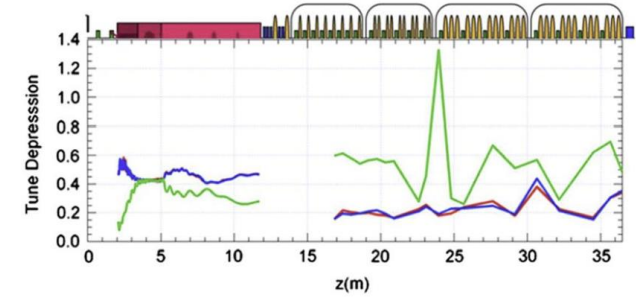


Fig. 4. Tune depression in the RFQ and the SRF-Linac.

IFMIF(~ 0.5)

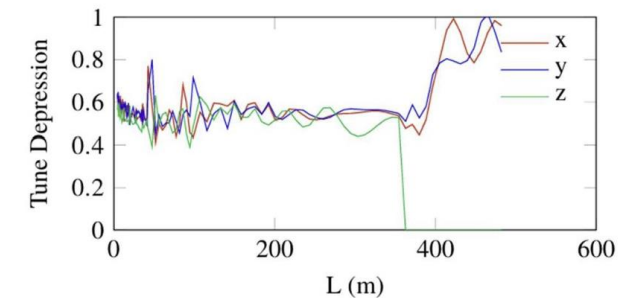


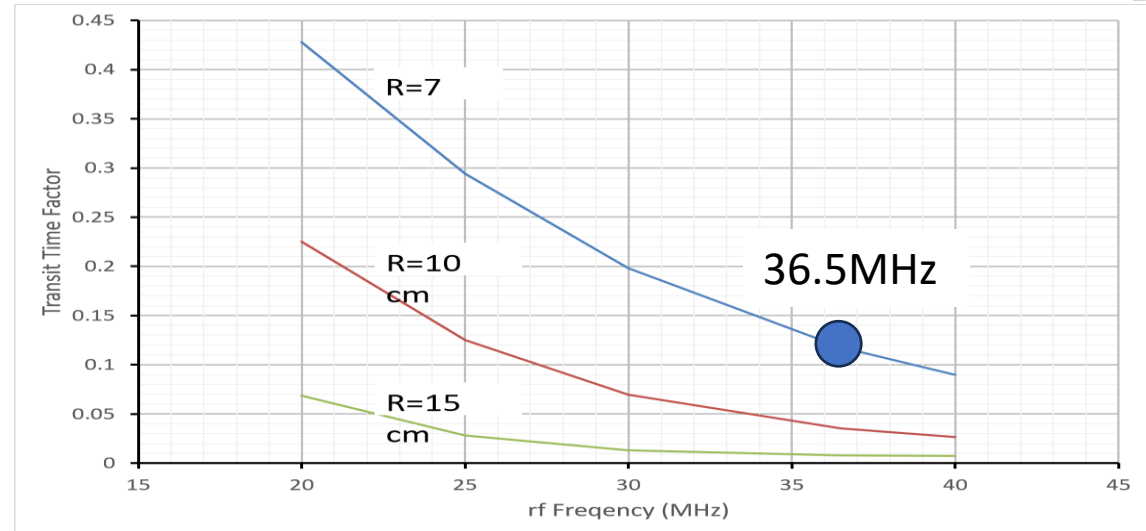
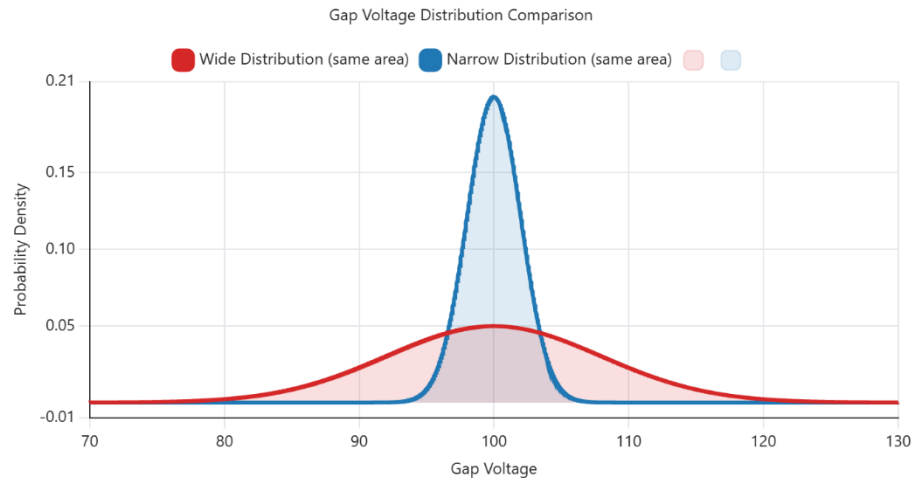
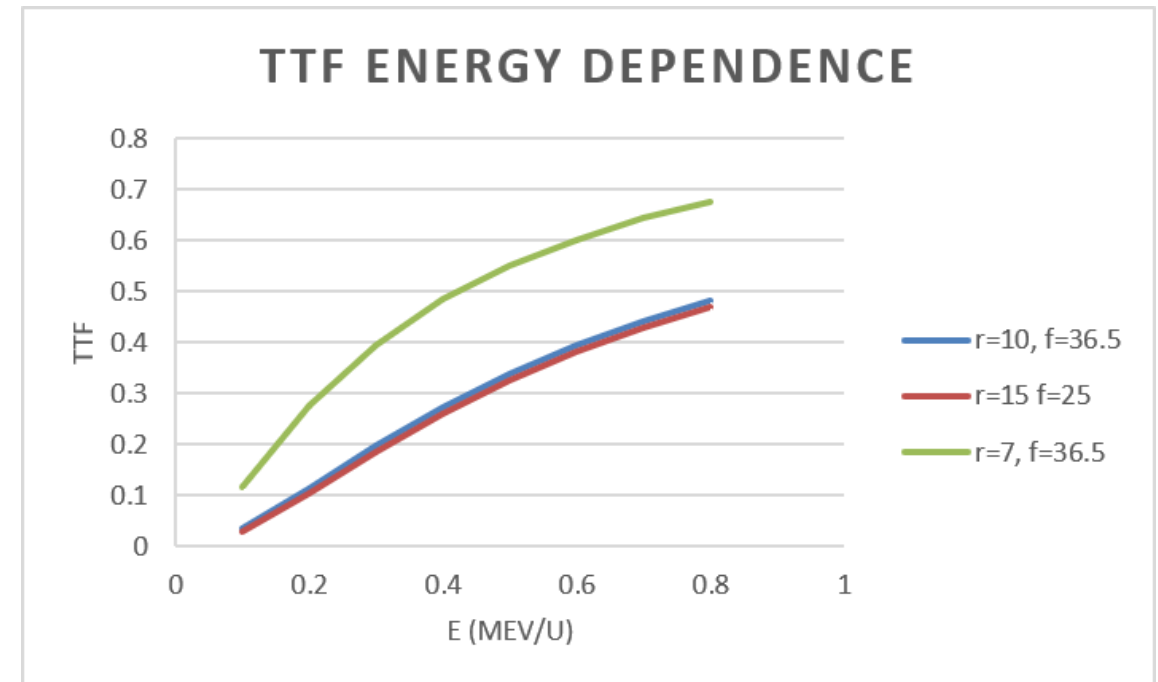
Figure 1: Tune depression in the ESS linac.

ESS(~ 0.6)



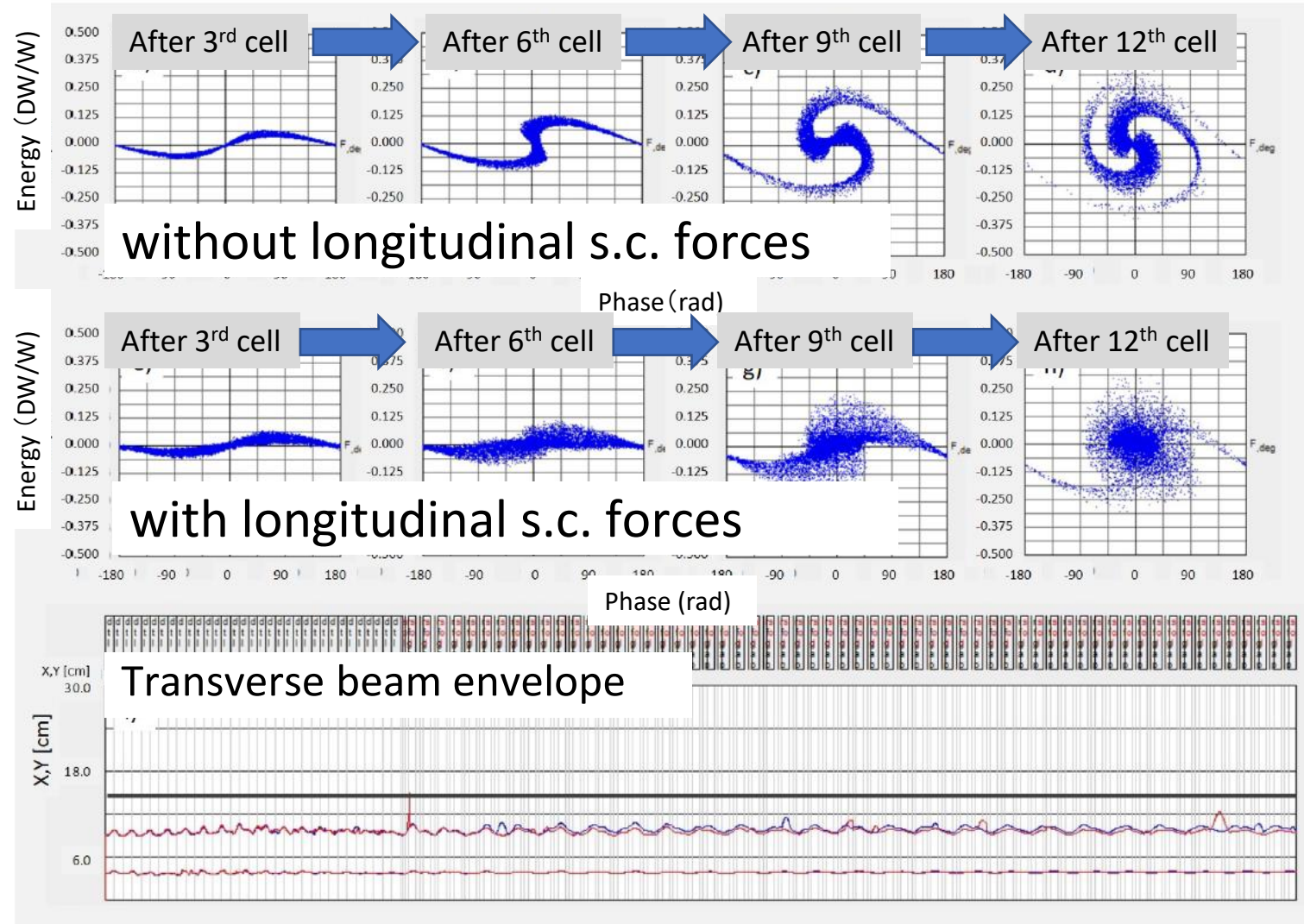
Problem of TTF (Transit Time Factor) at injection

Large bore $\rightarrow$ broad E distribution
 $\rightarrow$ Low rf frequency is required to
 $\rightarrow$ keep TTF larger

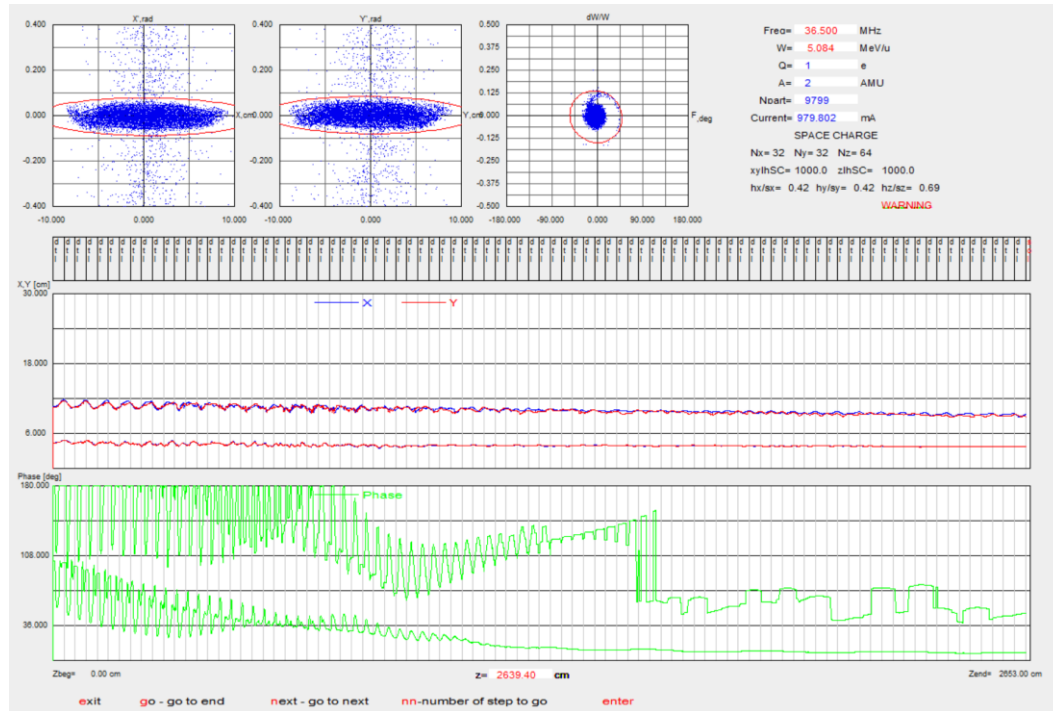
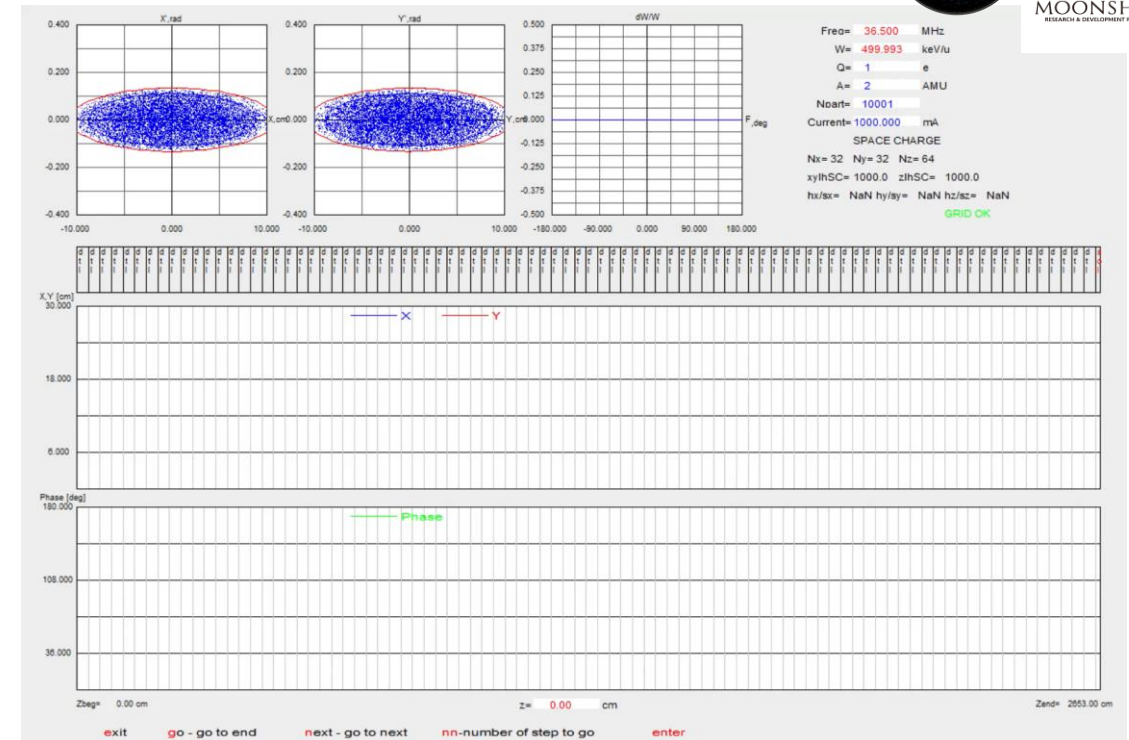


3D beam envelope simulation in the low β section

TRACK code (developed by P. Ostroumov, et al.):
that includes the space charge effect and non-linear phenomena owing to this effect



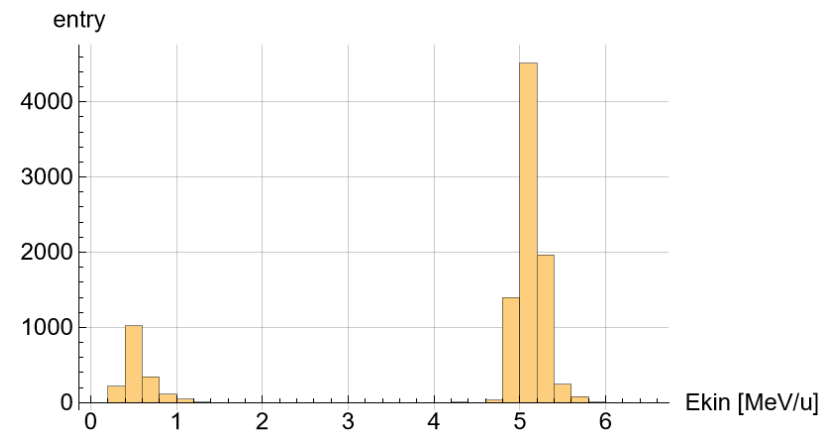
3D beam envelope simulation in the low β section



Normalized RMS emittance $25\pi\text{mmmmrad}$

Injection Energy 1MeV

Acceleration efficiency 82.4%



To reduce the length of the low-beta section.

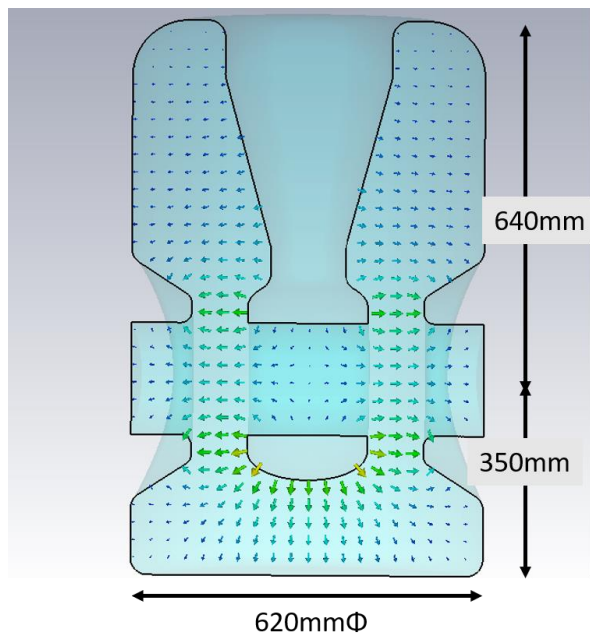
- **Increase Injection (200keV → 400keV, 1000keV)**
 - Improve small TTFs
 - Improve efficiency (Cell length (40cm) > $\beta\lambda/2$ (~8cm) at 200keV injection)
- **IH linac in solenoid or giant RFQ will be study**
- **These studies are going**

Medium β section (10-40 MeV)

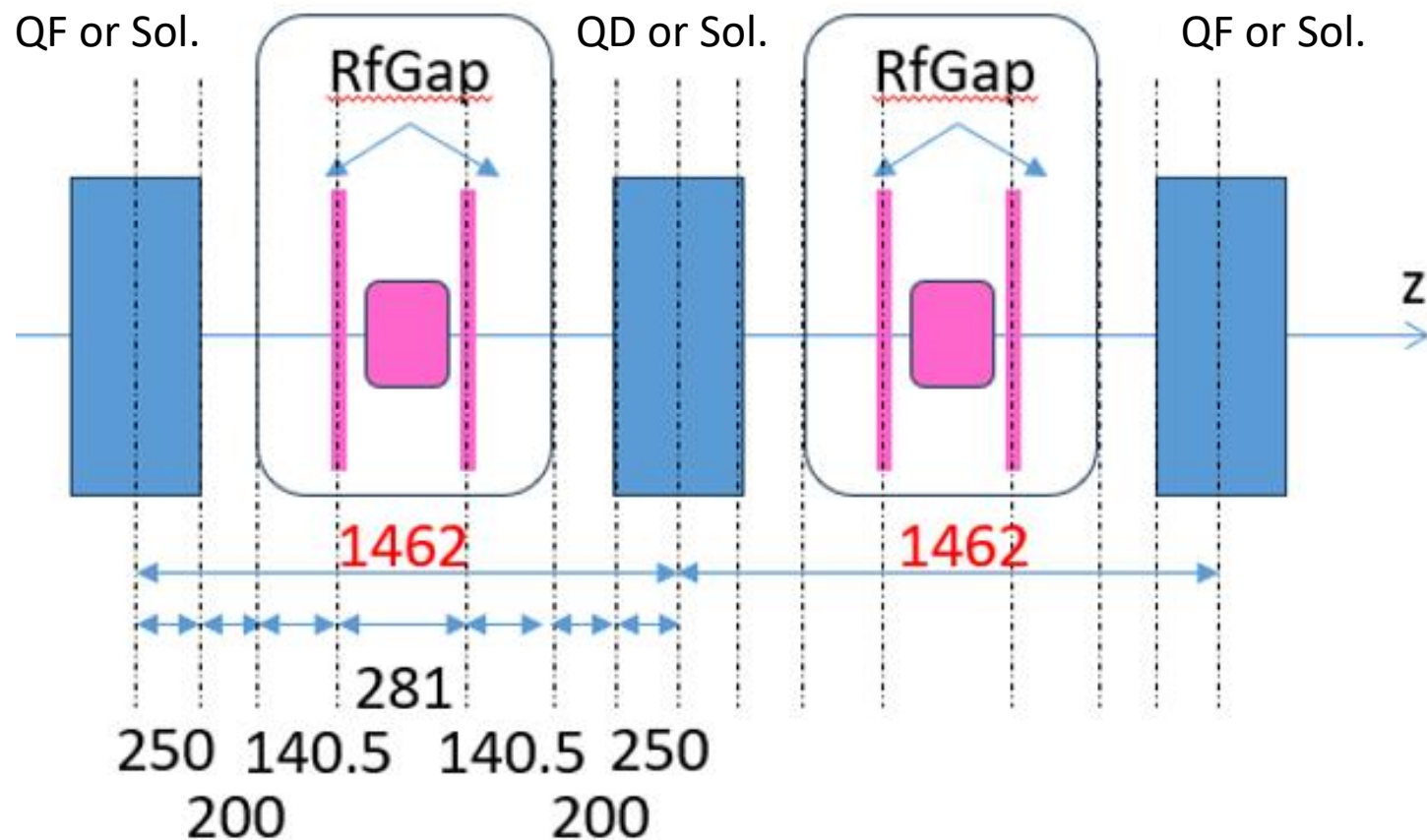


Structure of the cavity (30 quarter-wave resonator until 40MeV)

QWR 73MHz



Beam bore 200mm ϕ

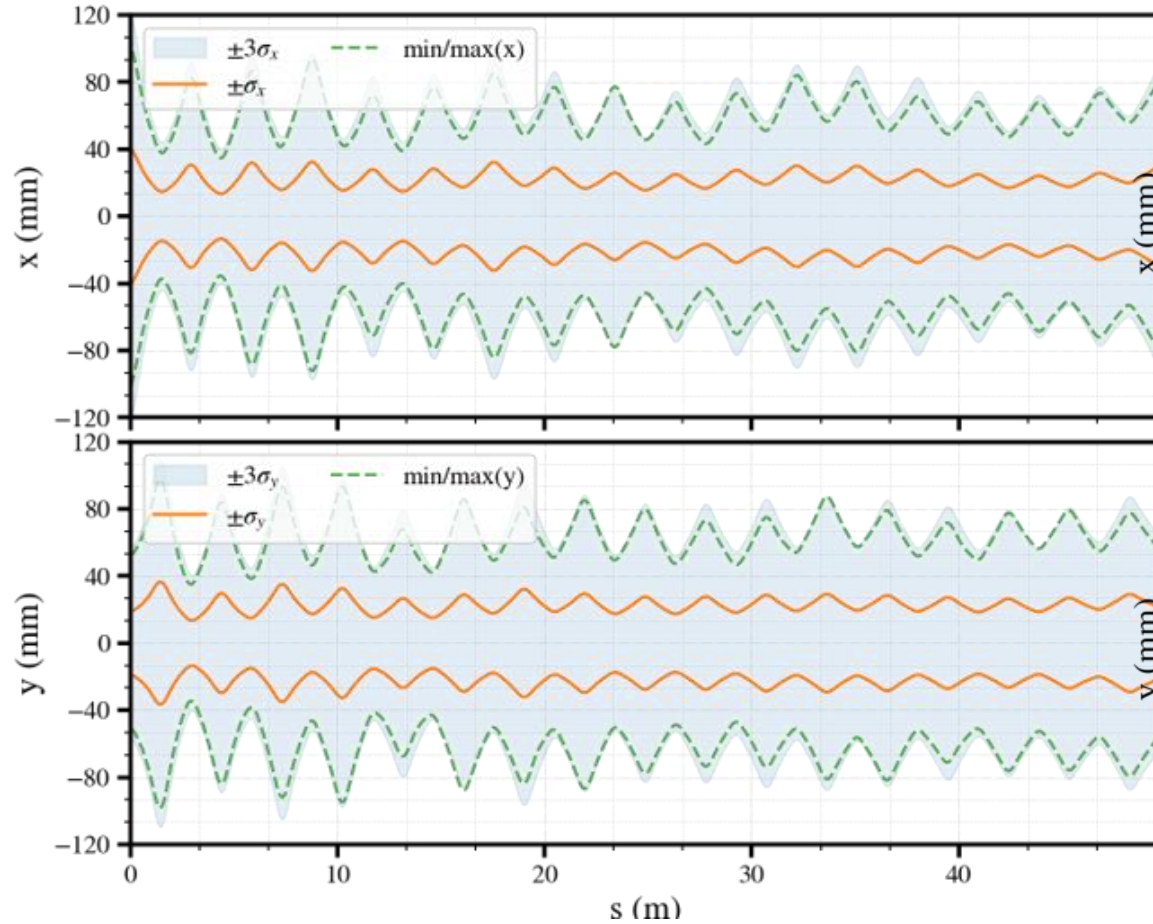


単位:[mm]

FODO lattice vs Solenoid based lattice (IMPACT-X)

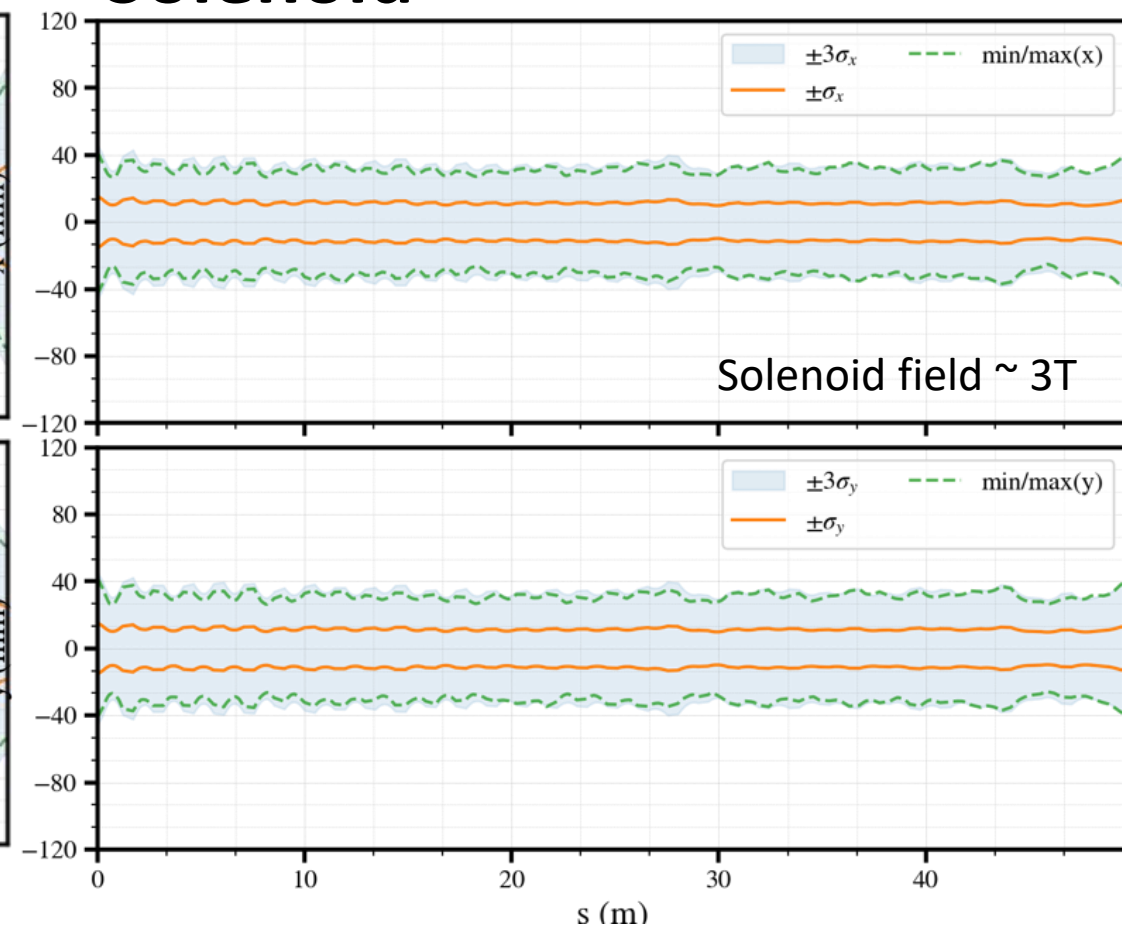


FODO



Beam pipe= $5 \times \sigma_{rms} \sim 300\text{mm}$

Solenoid



Beam pipe= $5 \times \sigma_{rms} \sim 120\text{mm}$

Design study of Superconducting Cavity started with
the bore from the **solenoid based lattice**

17 Halo Analysis and Suppression Toward Completion of the 1A Linac Design



Objective

- Halo analysis and suppression for both **low-beta** and **medium-beta** sections
- Beam dynamics simulation with approximately **10^8 macro-particles**
- Support the **completion of the 1 A linac design**

Physics Issues to be Studied

1. Coherent Resonance

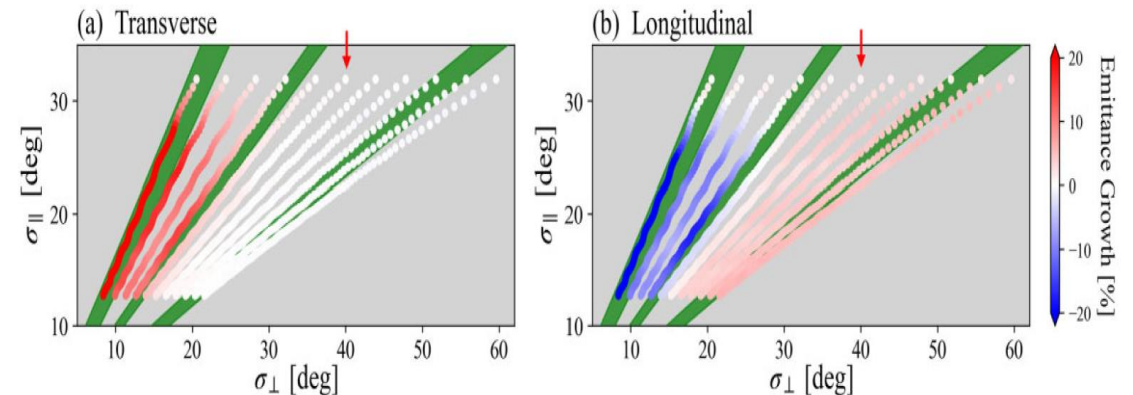
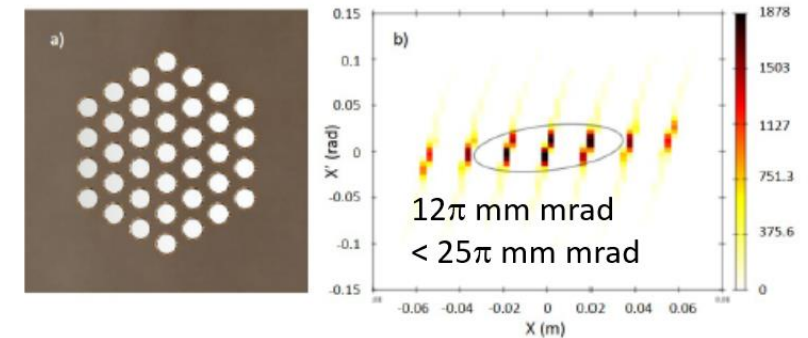
- Check coherent resonance using Stop Band Diagram
- Identify mechanisms of halo formation
- Evaluate impact on beam loss and emittance growth

2. LEBT and Mismatch Effects

- Investigate halo generation due to **Multi-hole LEBT**
- Study beam mismatch at section transitions
- Quantify contributions to halo growth and beam degradation

Expected Outcome

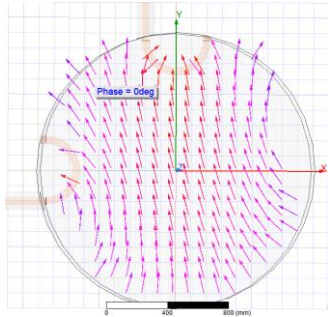
- Understanding of dominant halo formation mechanisms
- Validation of beam dynamics design with large-scale simulations
- Establishment of halo suppression strategy for the 1 A linac



CARA (cyclotron auto-resonance Accelerator) sorry for not linac but cyclotron



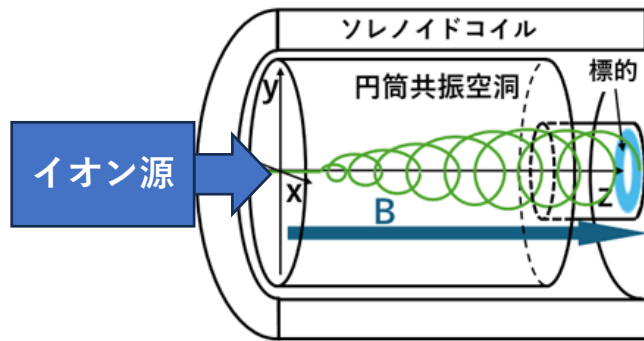
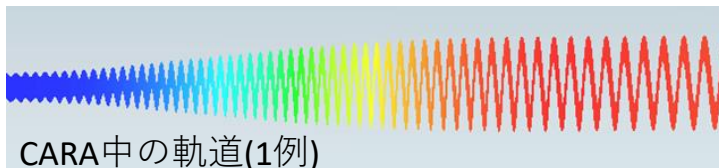
TE111 in the resonator



Cyclotron resonance frequency

$$\omega = \frac{v}{\rho} = \frac{qB}{m}$$

- Cyclotron frequency = Resonance frequency
→ Resonant acceleration is achieved
- By utilizing a helical beam trajectory, this concept enables compact CW-beam acceleration while mitigating space-charge effects in high-current, low-energy beams.



Background

1. This acceleration concept was proposed in the 2000s by Hirshfield and colleagues at Yale University. The original concept targeted beam energies of approximately 1 GeV.
2. Its realization has been hindered by the requirement for a large-aperture, high-field solenoid magnet. Although the concept has been experimentally demonstrated with electron beams, it has not yet been realized for high-current ion beams.

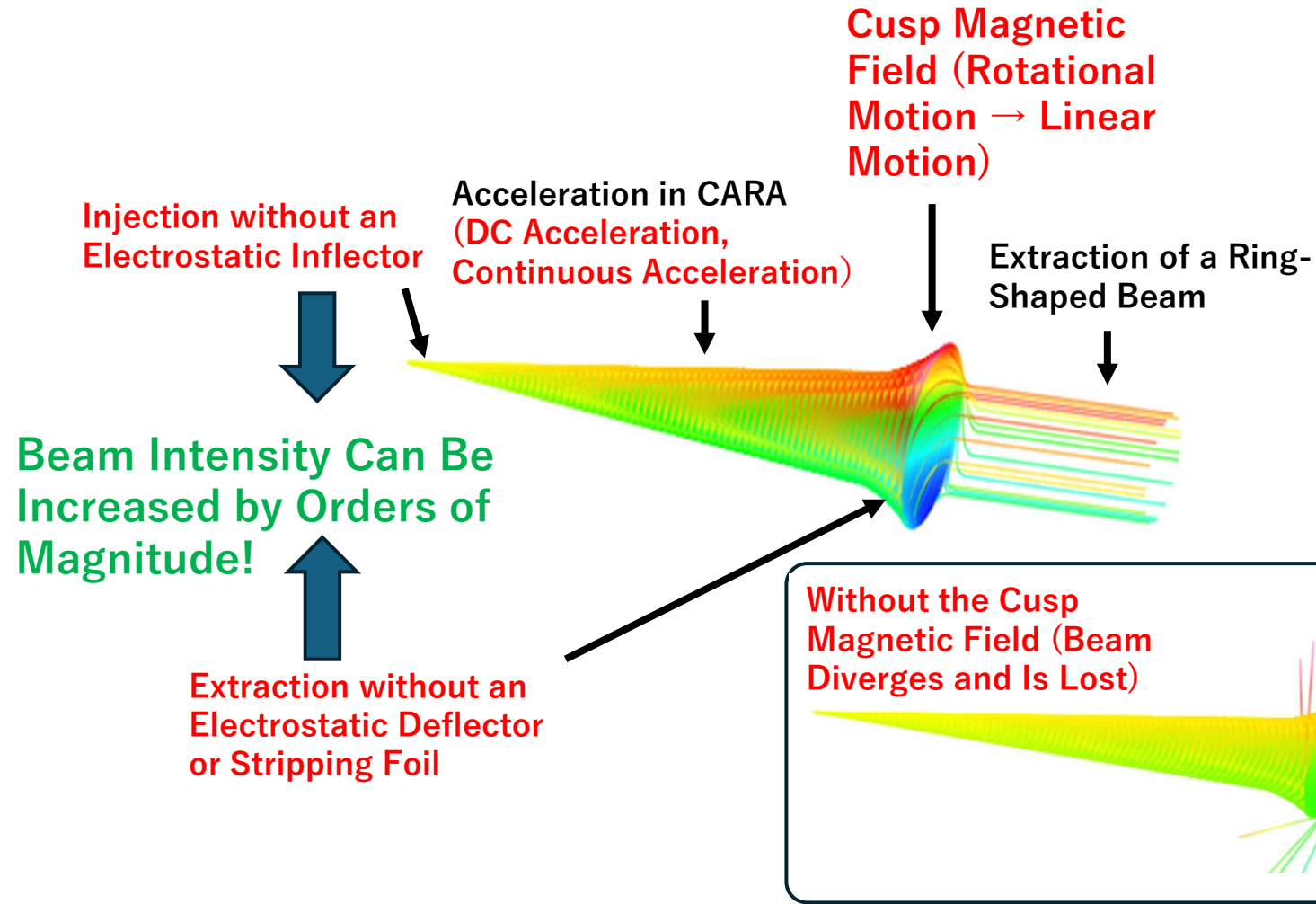
In the present

3. project, the goal is to demonstrate the concept in the non-relativistic energy regime up to approximately 1 MeV (40MeV deuteron).

Key Features

1. Mitigates space-charge concentration in the low-energy section of the accelerator.
2. Enables acceleration of a continuous-wave (CW) beam without bunching, thereby alleviating space-charge effects.
3. Beam extraction without disperse is difficult
4. Provides a compact beam trajectory, with the kinetic energy imparted in the direction tangential to the circular orbit.

Beam Extraction Method from CARA

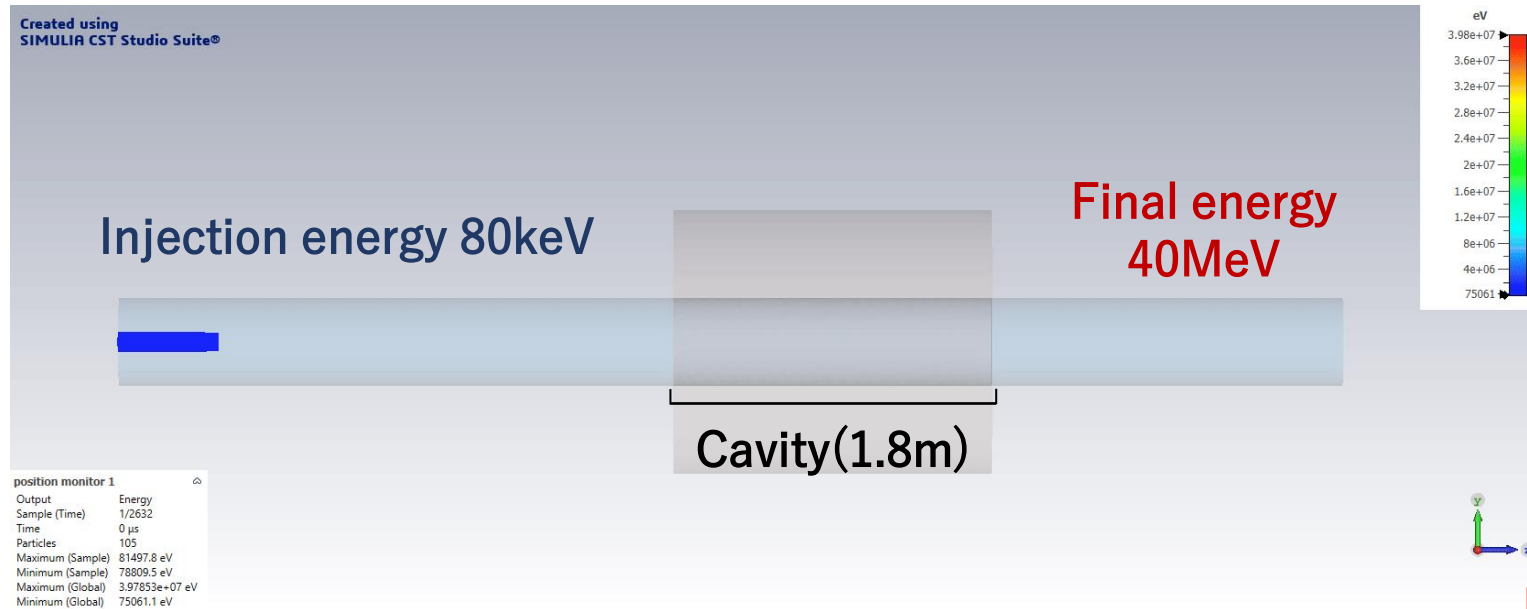
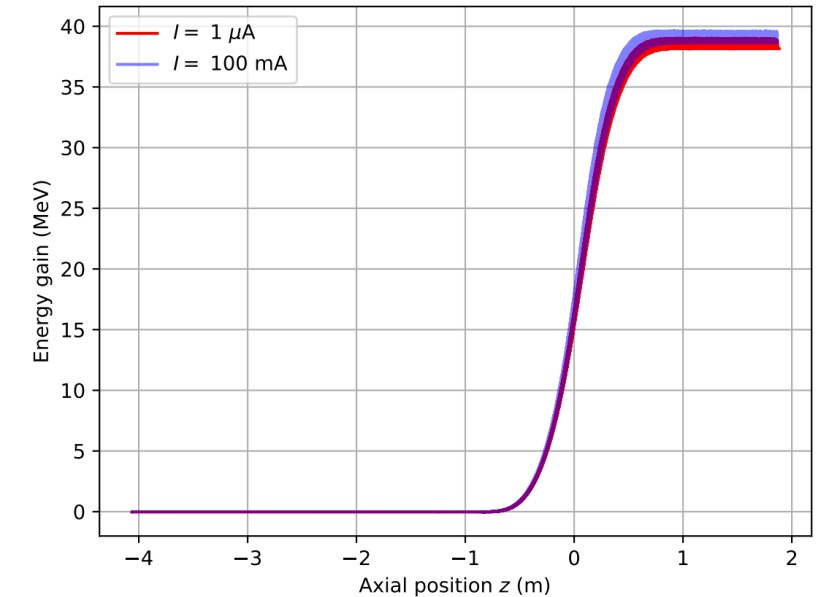


RIKEN SRC (Superconducting Ring Cyclotron) Beam Extraction Port: 12 mm

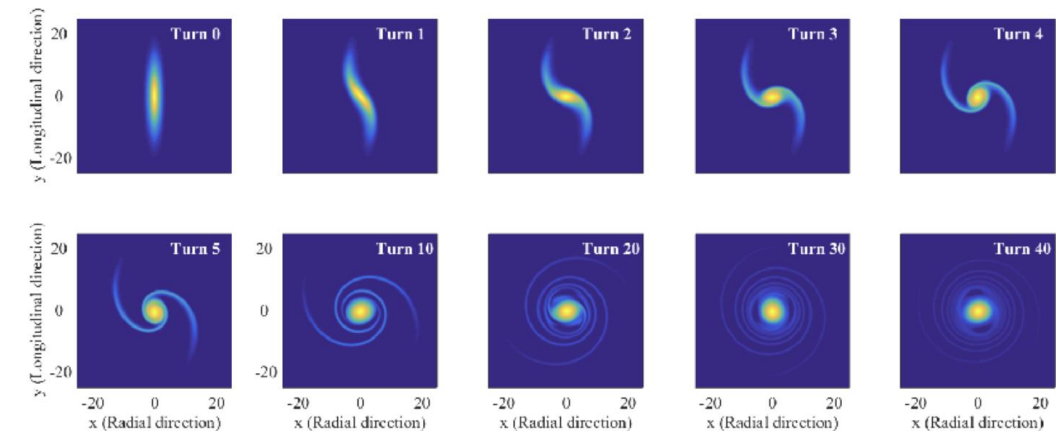
dCARA (40MeV, 100mA!!, deuteron)



7T, 53.4 MHz (CST studio)



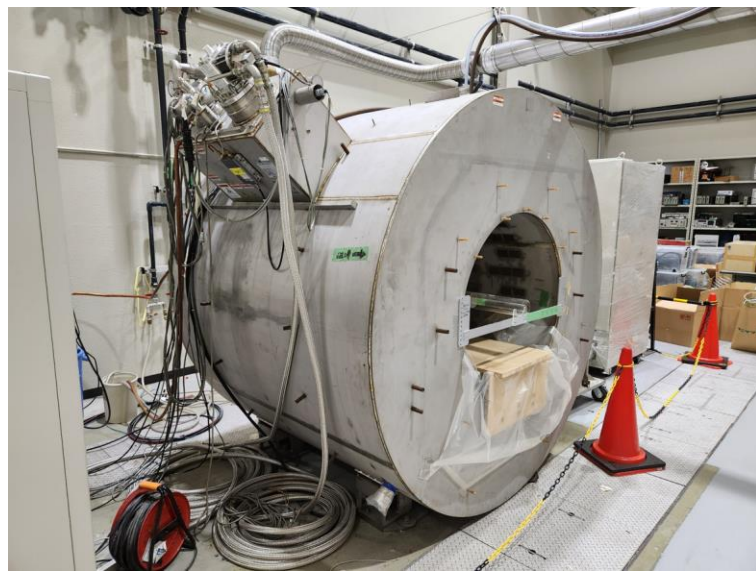
Round beam in PSI injector 2 cyclotron



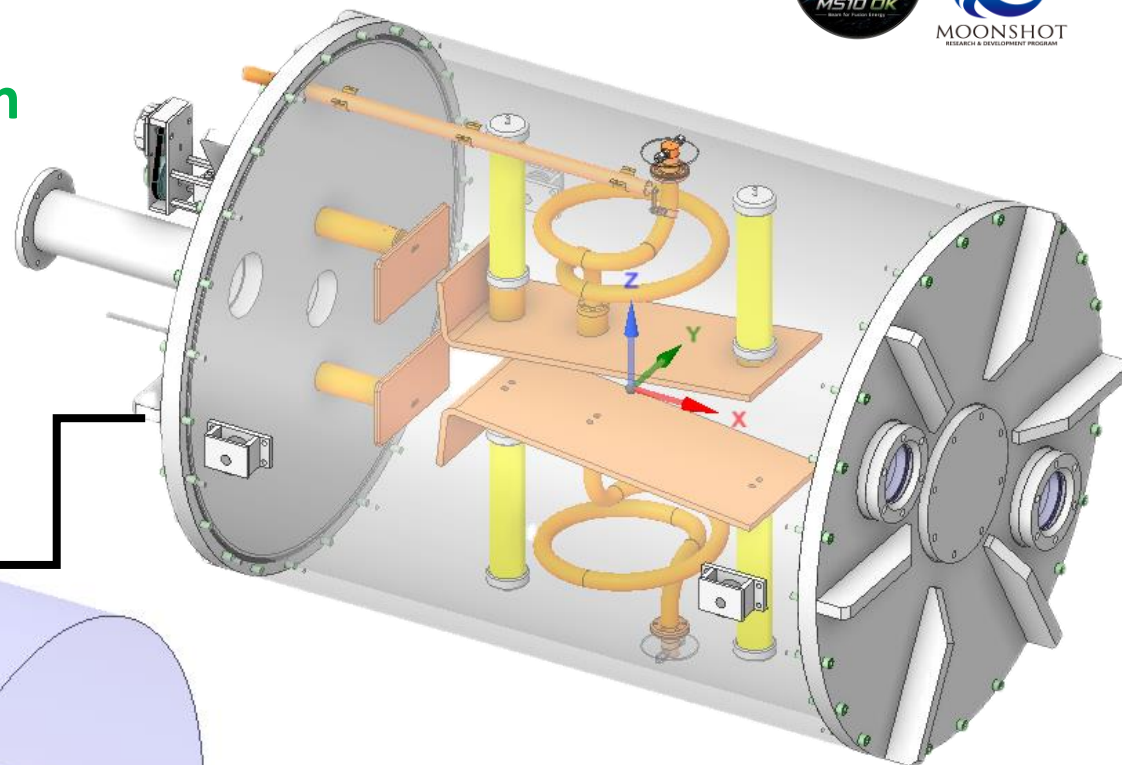
DONES length 40m、 dCARA length 1.8m

We are investigating why CARA is capable of accelerating such high-intensity beams and evaluating its beam stability.

Ion CARA verification test (World's first)

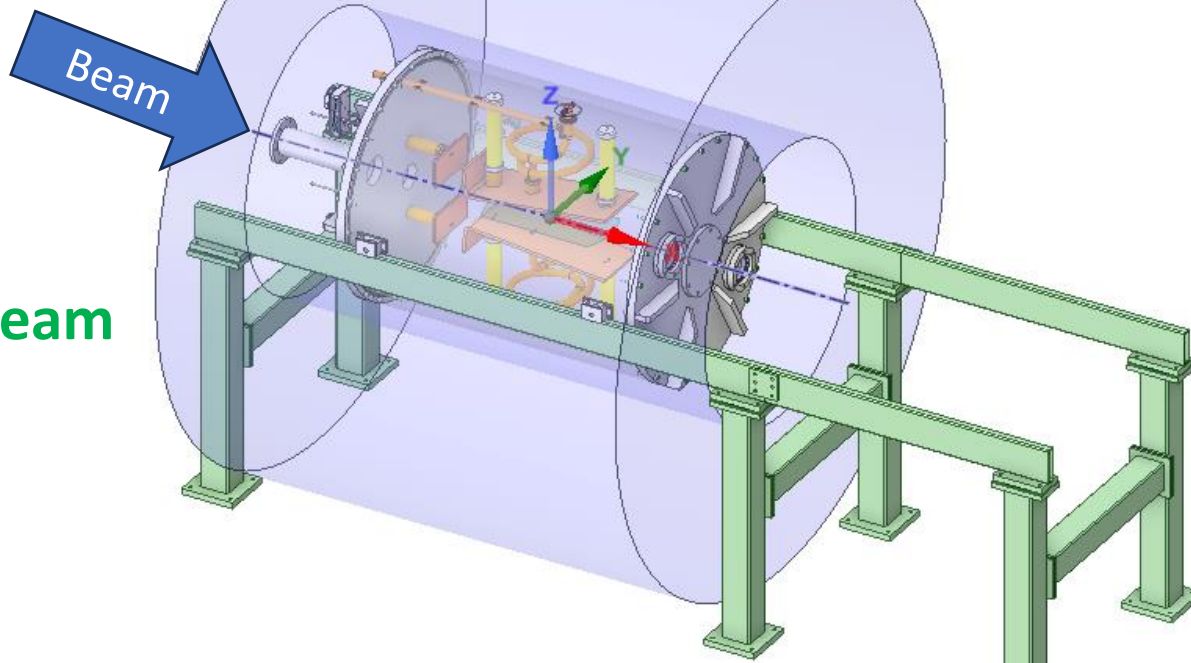


1MeV 1mA proton



Recycled 3T MRI magnet

We will have the first beam
in the autumn of 2027.



Resonator with a pair of
electrodes

Summary 1



**Fusion materials science requires 1 ampere class deuteron beams.
RFQs cannot handle such large apertures.
The single cell linac provides a scalable solution.
High tune depression ensures stability.
Halo suppression is a key research direction.
And CARA offers a complementary high intensity concept.**

Summary 2

Three talks in this session.

- **Jibong Hyun (QST):**
Reduction of longitudinal rms emittance through **nonlinear space-charge forces**
- **Abhishek Pathak (Fermi National Accelerator Laboratory):**
Space-Charge Stability and Beam-Loss Margins in the PIP-II Linac
- **Dong-O Jeon (Institute for Basic Science):**
Parametric instabilities in actual high-intensity linear accelerators

These three presentations focus on instabilities in space-charge-dominated beams, which are regarded as critically important research topics for advancing toward even higher beam intensities.

Hirokii Okuno

- 1: What is the current limit for RFQ for deuteron? (deuteron 500mA?)
- 2: Solenoid lattice or FODO lattice?
- 3: Polarity of Solenoid (+++++ or +-+-+-+ which is better?)
- 4: Why is the beam from CARA so stable?

Hyun Jibong

- 1: Can the predicted emittance reduction be confirmed experimentally?
- 2: Can this mechanism be applied for beam-quality control?
- 3: Can the concept of the force nonlinearity parameter be extended to predict beam halo formation?

Abhishek Pathak

Dong-O Jeon

My question is whether parametric instabilities are observable in actual circular accelerators, especially high order ones. As I shall present tomorrow, high order parametric instabilities are not observable in actual linear accelerators.