Design study of a Split-Coaxial RFQ for IsoDAR

Jungbae Bahng

Korea University / Massachusetts Institute of Technology

ICHEP 2018, Seoul, Korea

July 6th, 2018

Massachusetts Institute of Technology

KOREA UNIVERSITY

Outline

- Introduction & Motivation of the IsoDAR project
- Accelerator system for the IsoDAR
  - Layout of the IsoDAR project
  - IS & LEBT / Spiral Inflector / Cyclotron
- RFQ design
  - Briefly Principle of a RFQ
  - Considerations
  - Design results and features
- Next step & Summary

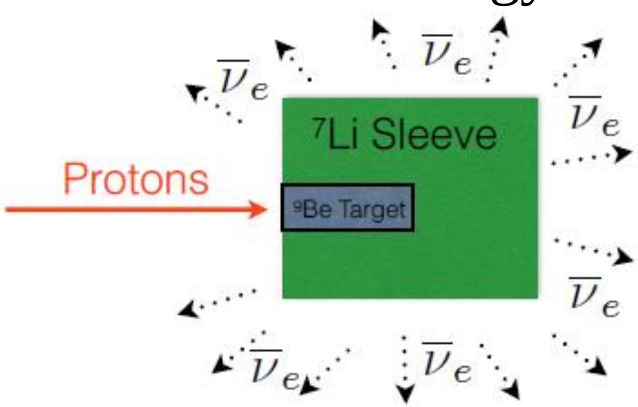
Introduction & motivation

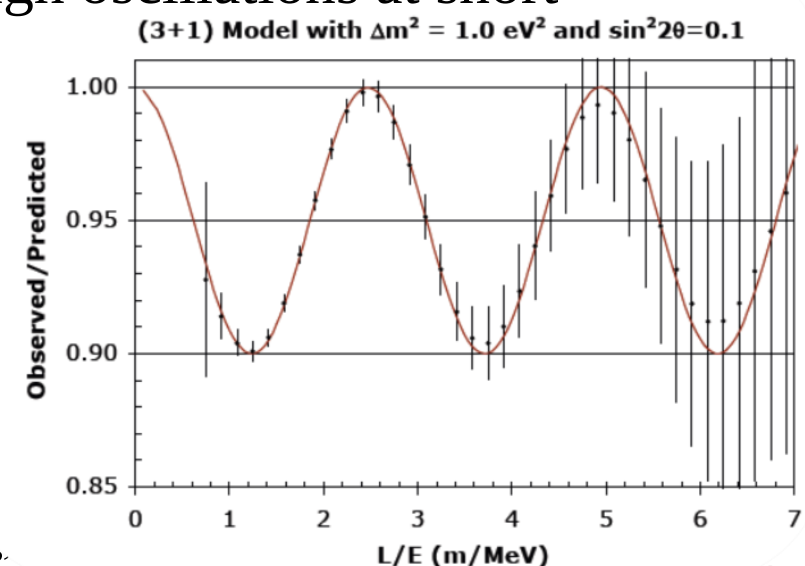
- IsoDAR (Isotope Decay-At-Rest Experiment) will be the first stage of DAEδALUS, utilizing the DAEδALUS Injector Cyclotron (DIC) to search for physics beyond the standard model.
- Two main scientific goals :

– Sterile neutrino searches

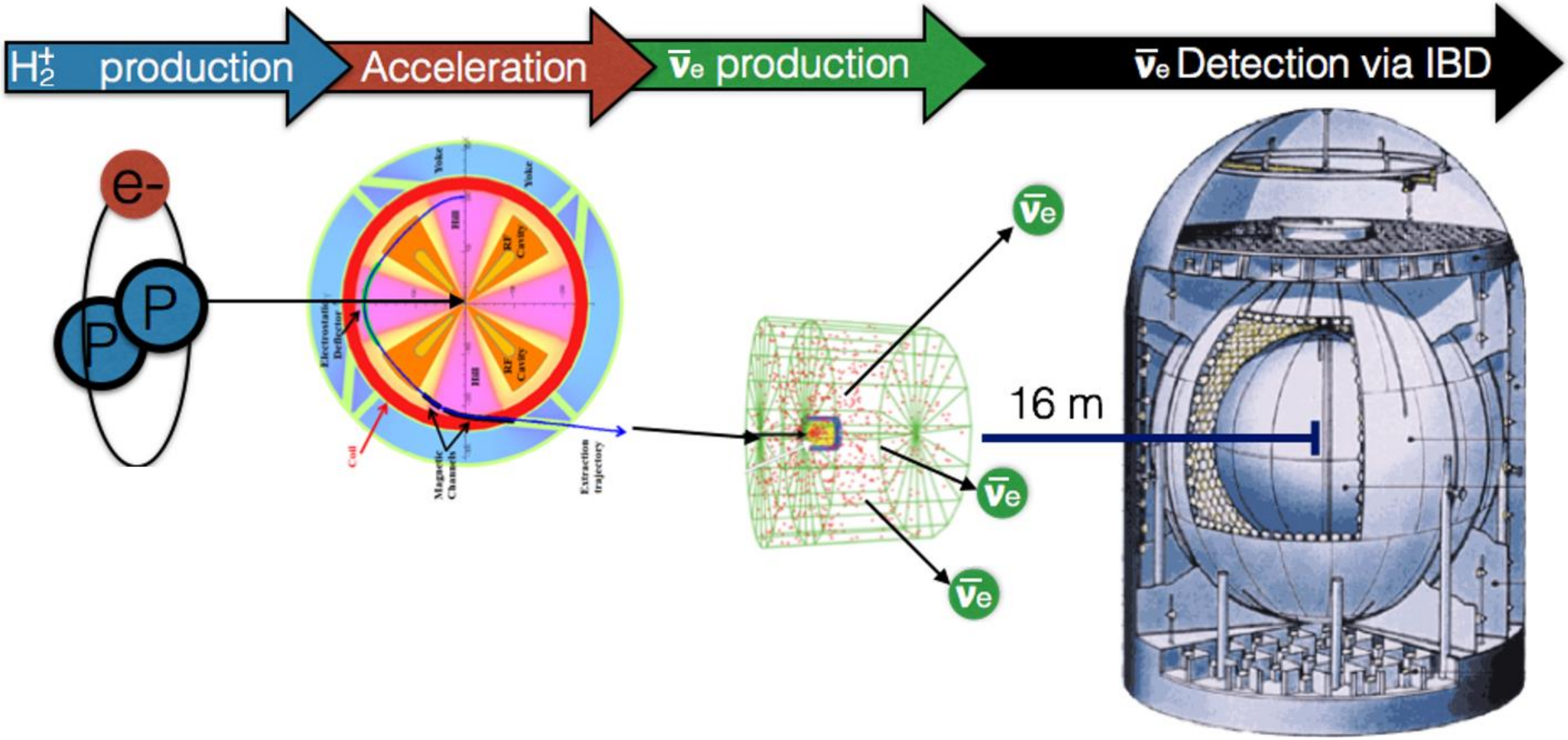
– Non-standard interaction searches

- Search for sterile neutrinos through oscillations at short distance and low energy





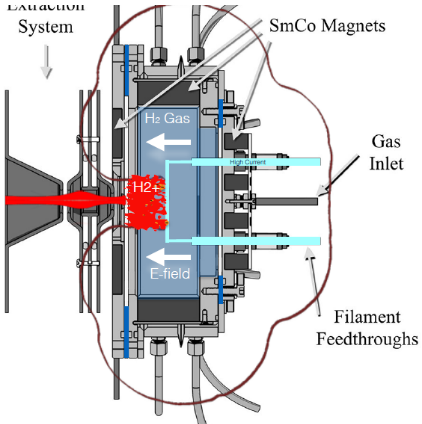
Introduction & motivation



IBD : Inverse Beta Decay

Layout of the IsoDAR accelerator system

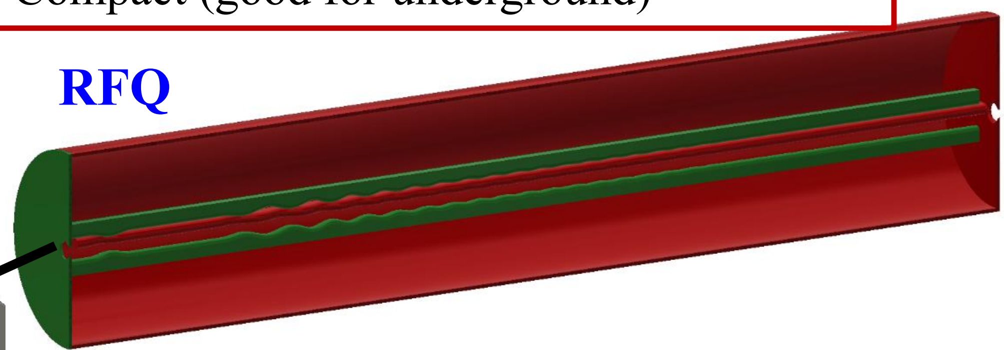
Ion source / LEBT



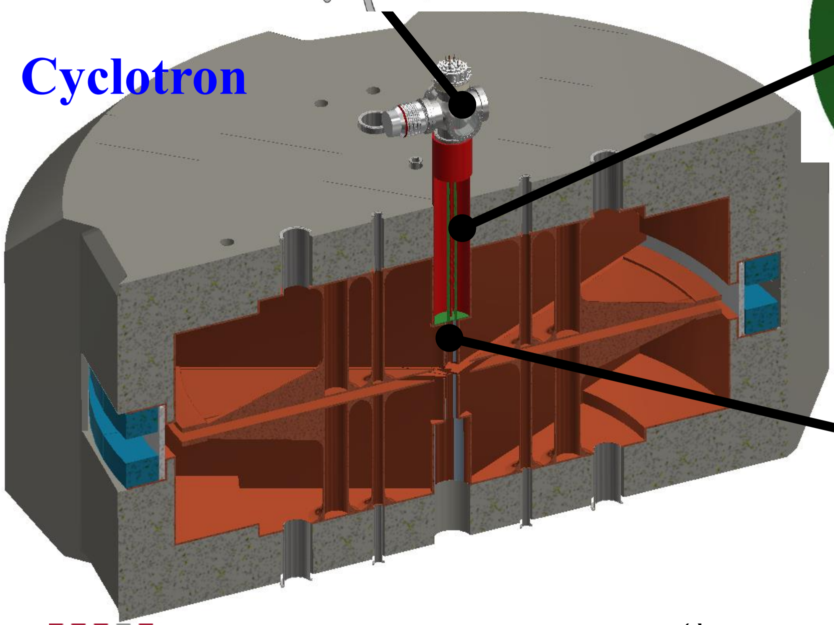
RFQ-Direct Injection Project (RFQ-DIP)

- Highly efficient bunching
- Sorts out protons
- Accelerates to injection energy of 70 keV
- Compact (good for underground)

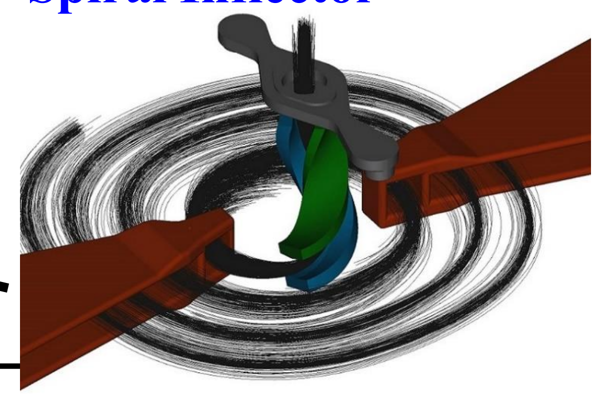
RFQ



Cyclotron

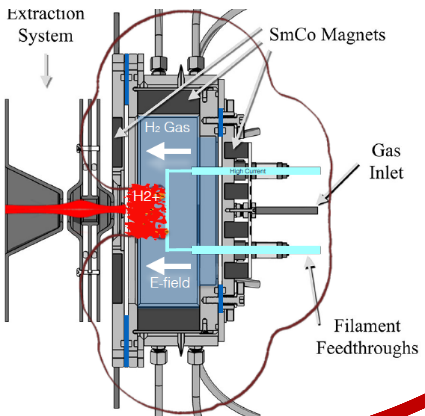


Spiral Inflector



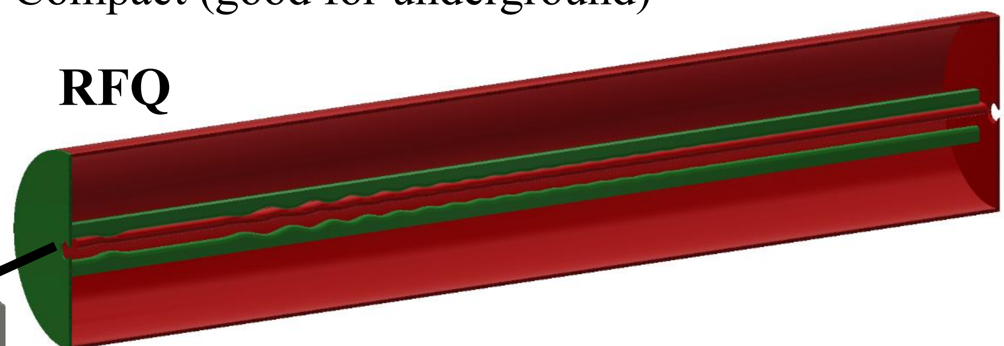
Layout of the IsoDAR accelerator system

Ion source / LEBT

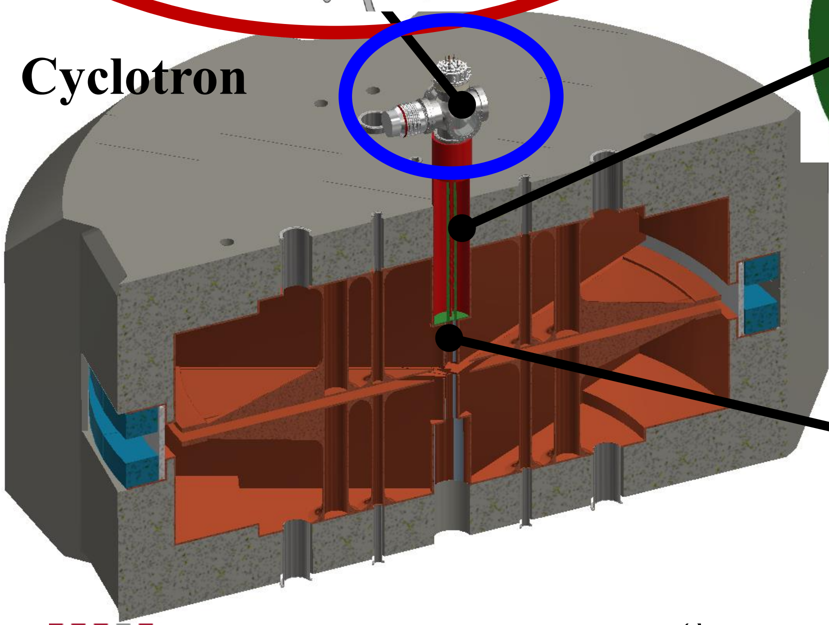


RFQ-Direct Injection Project (RFQ-DIP)
- Highly efficient bunching
- Sorts out protons
- Accelerates to injection energy of 70 keV
- Compact (good for underground)

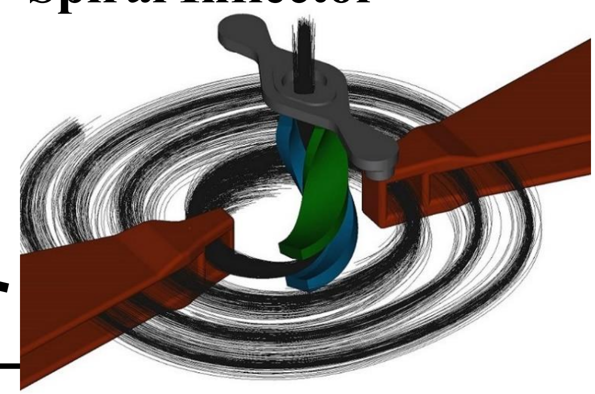
RFQ



Cyclotron



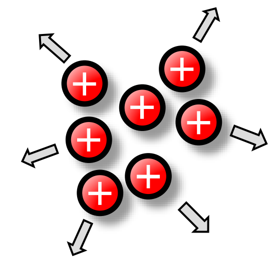
Spiral Inflector



Why we choose H_2^+ ion beam

- 10 mA of protons do not want to be crowded together in a bunch! (Repulsive force)

$$E_x = \frac{1}{4\pi\varepsilon_0}\frac{3I\lambda}{c\gamma^2}\frac{(1-f)}{r_x(r_x+r_y)r_z}x, \qquad E_y = \frac{1}{4\pi\varepsilon_0}\frac{3I\lambda}{c\gamma^2}\frac{(1-f)}{r_y(r_x+r_y)r_z}y,$$



where, r_x, r_y and r_z are the semi-axes of the ellipsoid,
I is average current, f is a form factor (f are given by p and 1/p)

$$p \equiv \frac{\gamma \cdot r_z}{\sqrt{r_x r_y}}$$

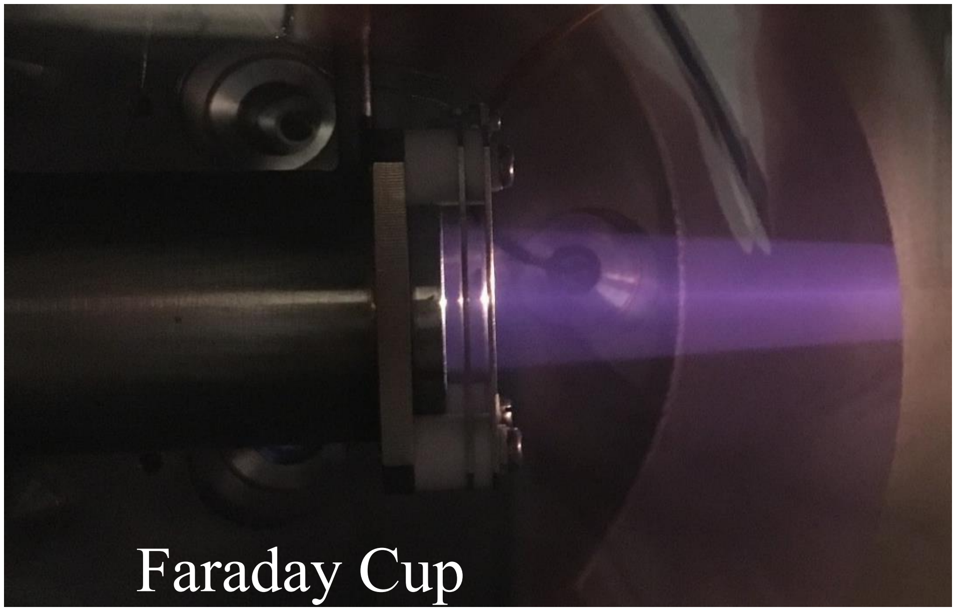
- Since high beam intensity and slow beam velocity, space charge effect makes emittance growth. ($F_{sc} \sim \gamma^{-2}$)
- In the low energy region, we need to consider carefully space charge effect

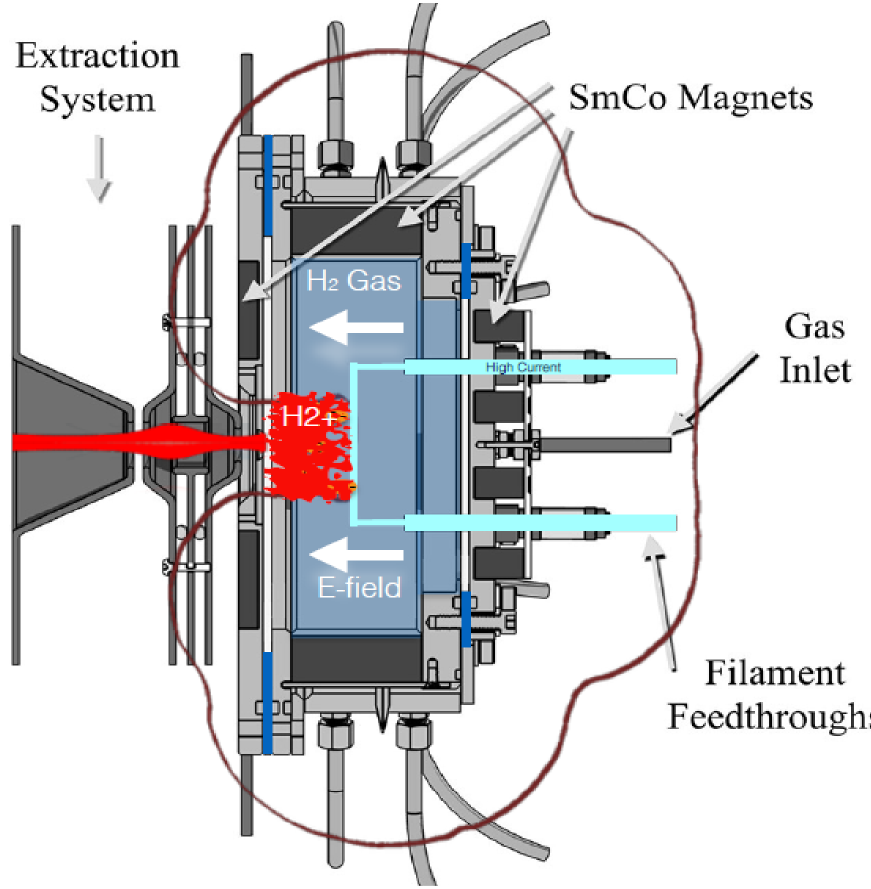
✓ Solution !

Two units of charge for one in the low energy region
Remove electron by stripping in the high energy region → get two protons

Helps with Injection and Low Energy Beam Transport

Ion Source

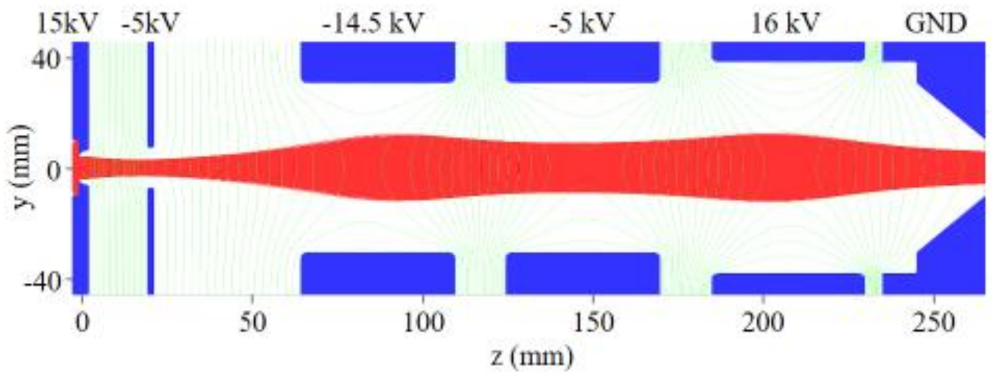




- Filament-Driven Multicusp Ion Source
- Based on: Ehlers and Leung: http://aip.scitation.org/doi/10.1063/1.1137452
- Currently commissioning at MIT (at the moment: **17 mA/cm²**)

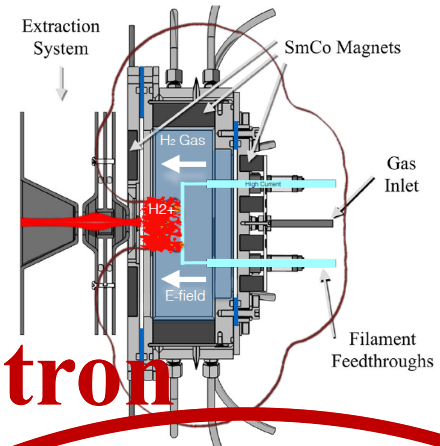
Extraction system for RFQ-DIP

- Preliminary simulation by Loyd H. Waites, Ph.D. student at MIT
- Simulation code : IBSimu
- Components : Two Einzel lenses
- Objectives : Matching beam parameters as the RFQ requirement
- Segmented for steering
- Next: Detailed simulation study & Technical design



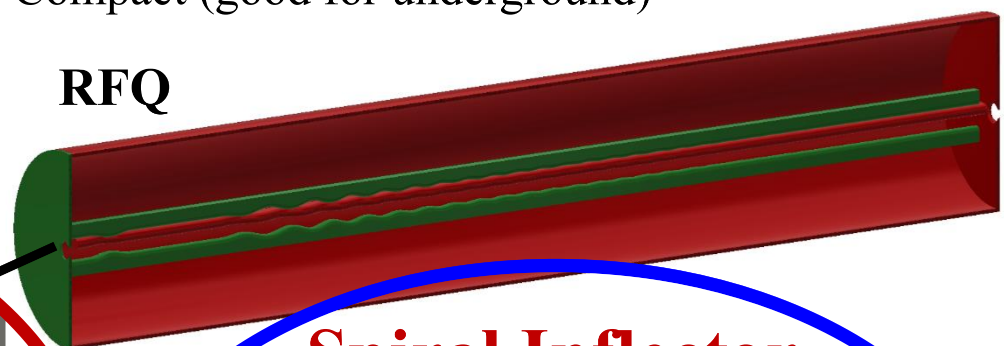
Layout of the IsoDAR accelerator system

Ion source / LEBT

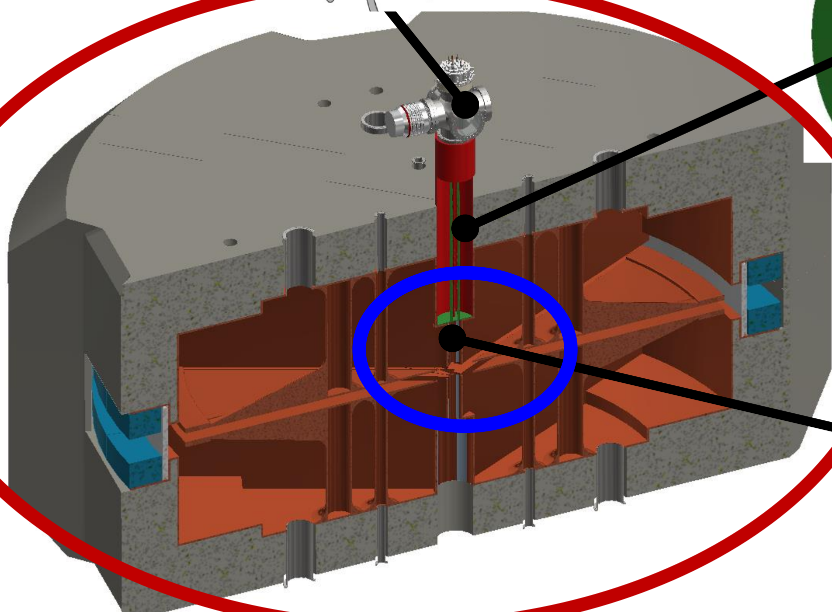


RFQ-Direct Injection Project (RFQ-DIP)
- Highly efficient bunching
- Sorts out protons
- Accelerates to injection energy of 70 keV
- Compact (good for underground)

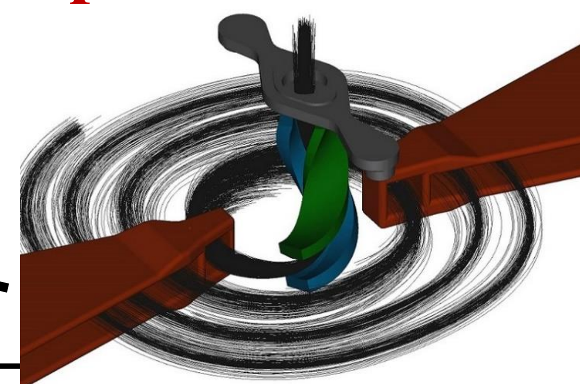
RFQ



Cyclotron

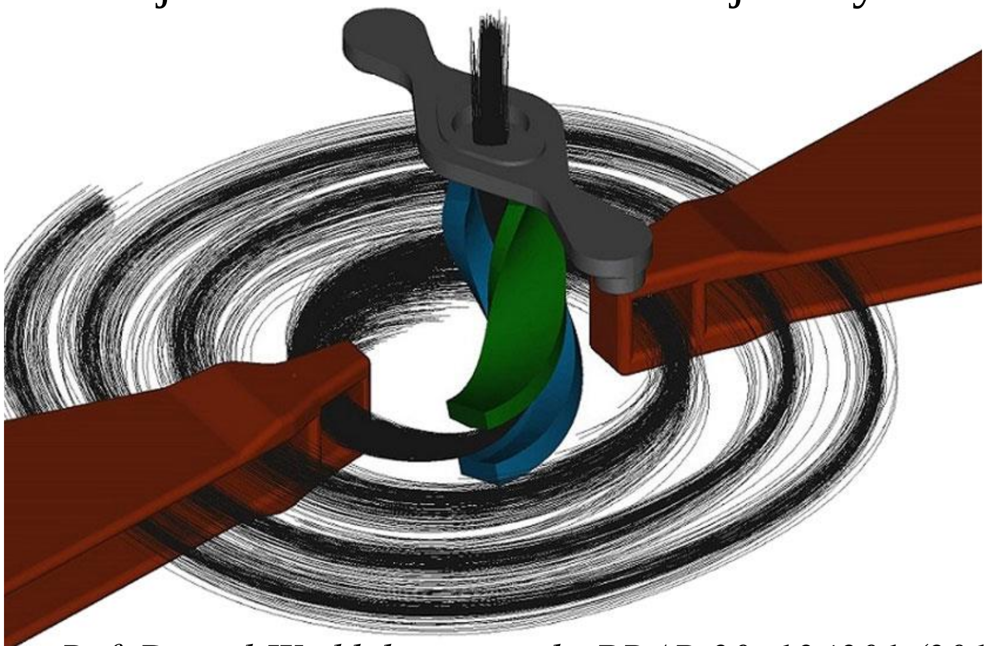


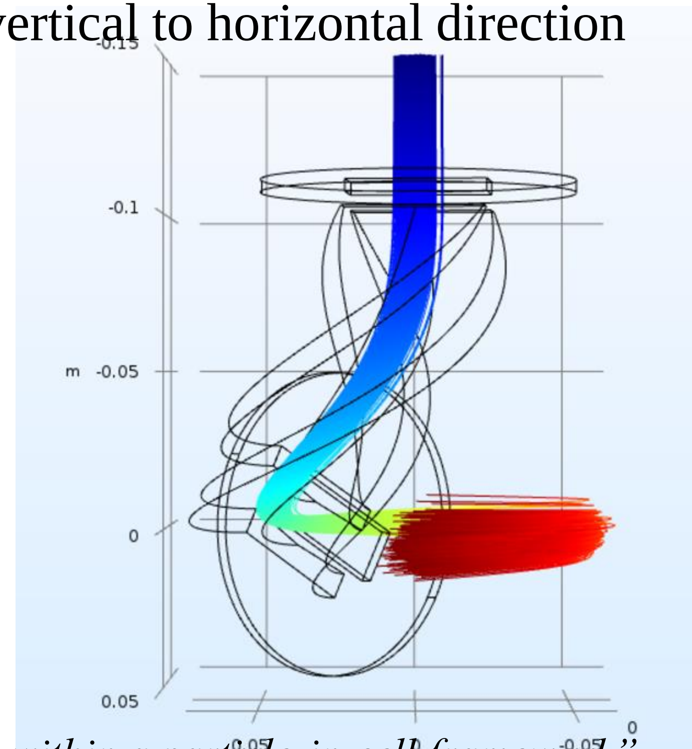
Spiral Inflector



Spiral Inflector

- Preliminary simulation by Daniel Winklenhner, Postdoc. at MIT
- Simulation code : OPAL and Inventor3D
- Structure : Twisted shape of electrodes
- Objectives : Convert beam trajectory from vertical to horizontal direction

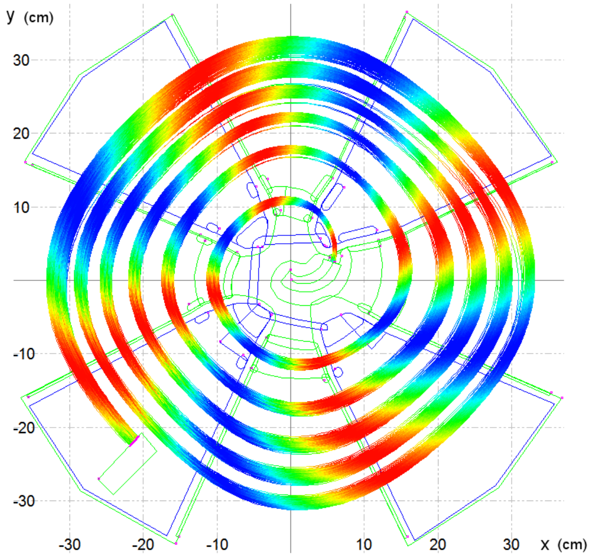


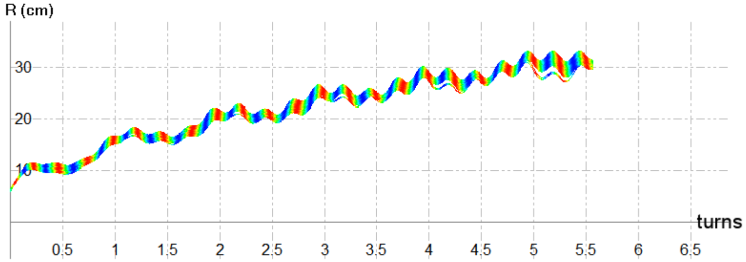


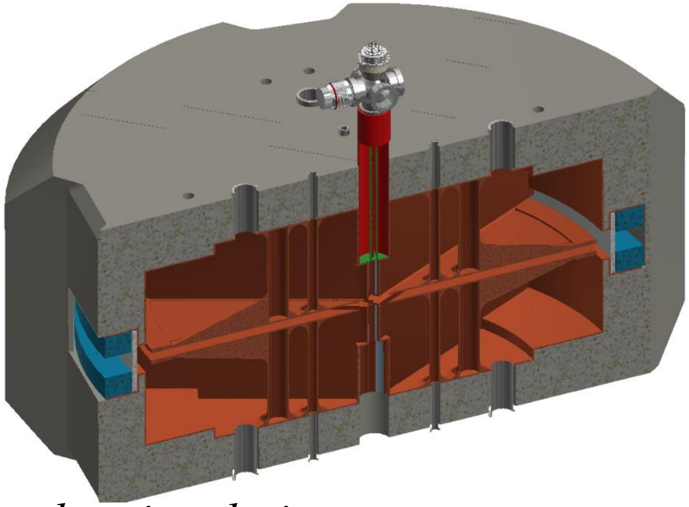
Ref. Daniel Winklehner, et. al., PRAB 20, 124201 (2017)
"Realistic simulations of a cyclotron spiral inflector within a particle-in-cell framework"

Cyclotron

- DIC is four-sector machine, with a pole radius of 220 cm, vertical gap of 10 cm to improve high intensity beam production.



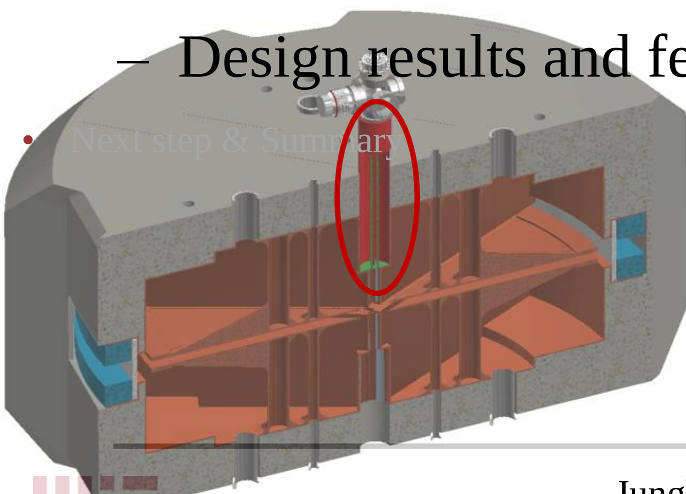




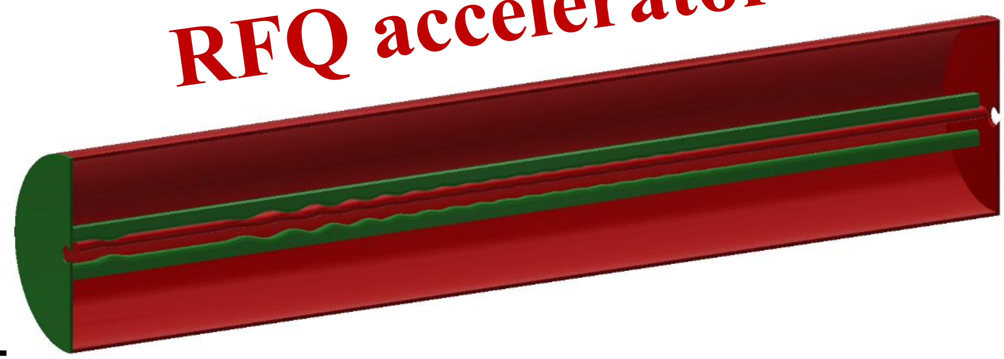
Ref. Cooperation with AIMA in France for central region design

Outline in RFQ design

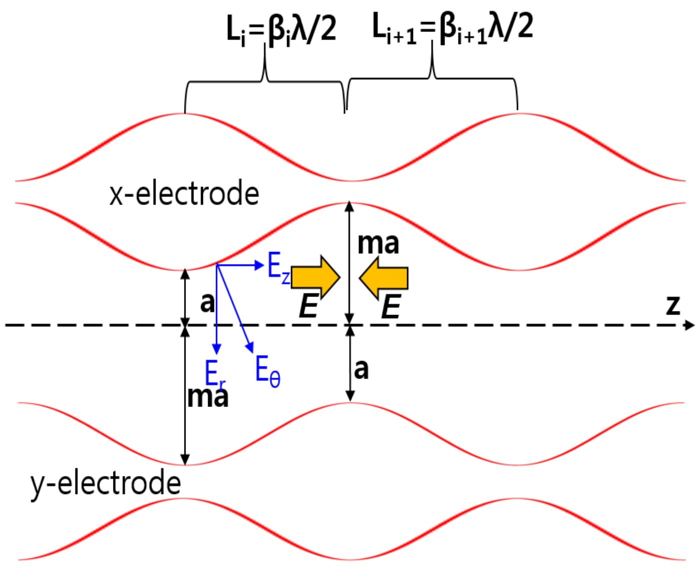
- Introduction & Motivation of the IsoDAR project
- Accelerator system for the IsoDAR
  - Layout of the IsoDAR project
  - IS & LEBT / Spiral Inflector / Cyclotron
- RFQ design
  - Briefly Principle of a RFQ
  - Considerations
  - Design results and features
- Next step & Summary

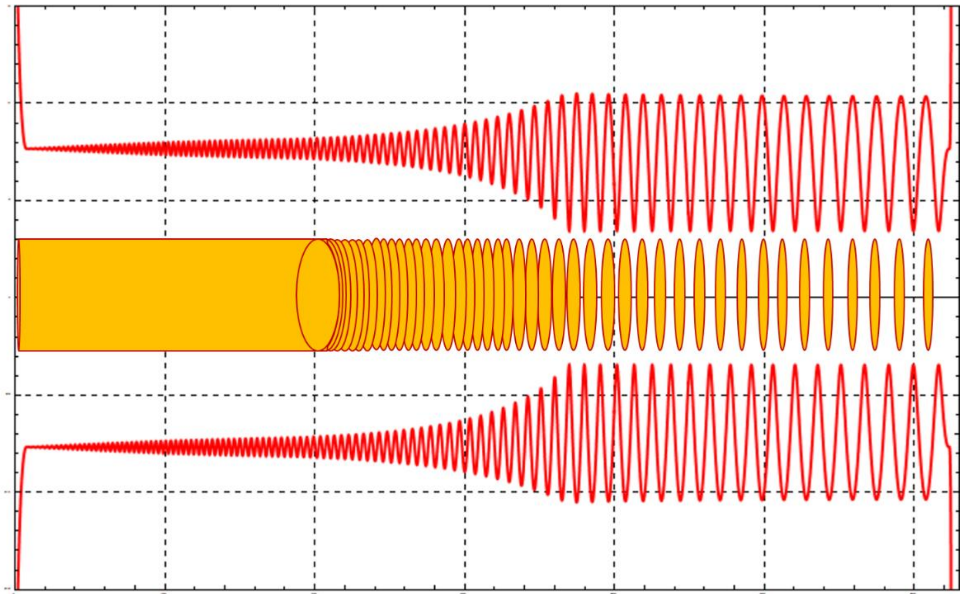


RFQ accelerator



Basic principle of an RFQ accelerator



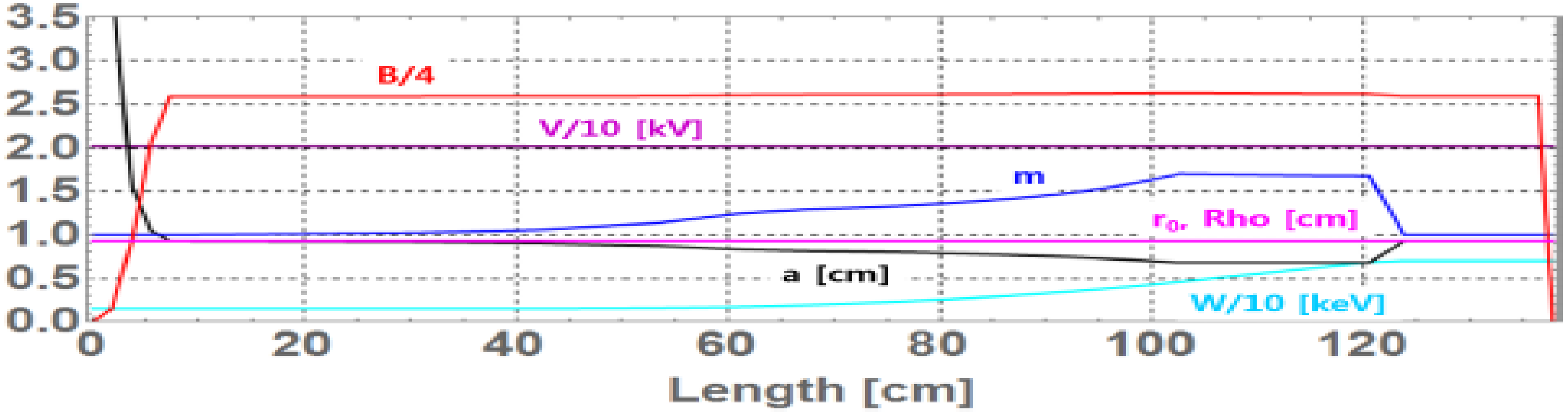


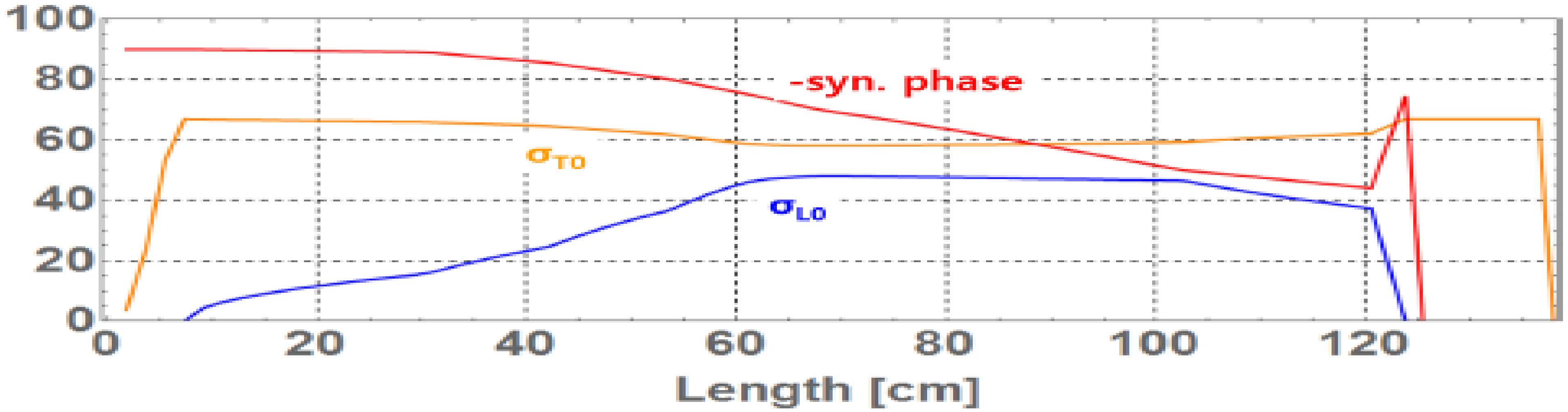
- Quadrupole electrode driven AC voltage, makes alternating transverse focusing like a FODO lattice.
- Perturbation in quadrupole electrodes makes longitudinal field for acceleration and bunching.
- The derivative longitudinal electric field makes longitudinal bunching and ion beam acceleration.

Considerations for the IsoDAR RFQ

Parameters	Value	Unit
Particle (A/q)	H_2^+ (2)	
Beam intensity @ target	10	mA
Operation frequency	32.8	MHz
Input beam energy	7.5	keV/u
Output beam energy	35	keV/u
Initial rms emittance	0.3	pi mm-mrad
Chamber diameter	**< 30**	**cm**
Longitudinal emittance	**< 42**	**pi keV-deg**
Length	**< 150**	**cm**

Design parameters in the RFQ



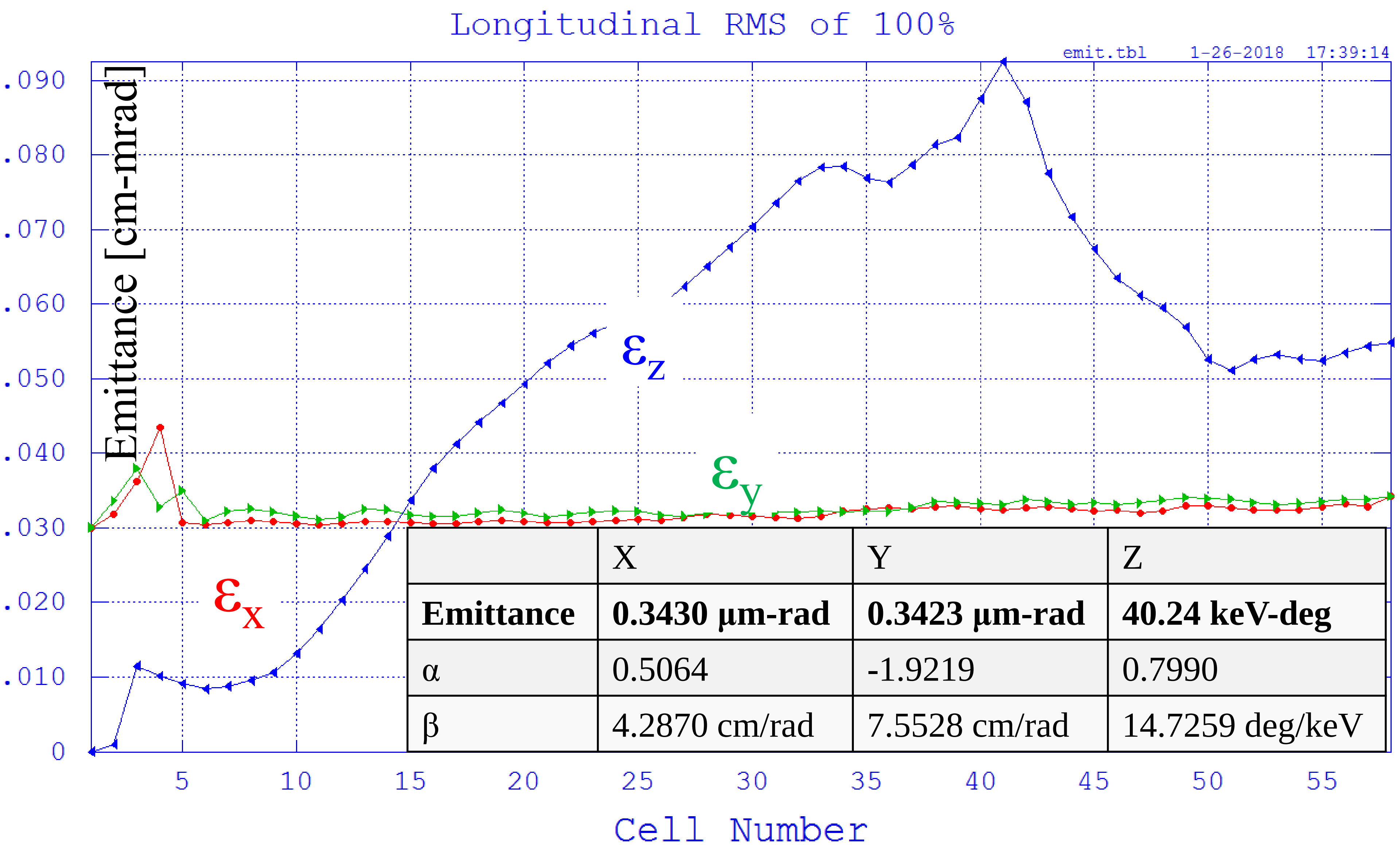


Design results of the beam dynamics

Elements	**Unit**	**Design parameters**
Frequency	MHz	32.8
Particle	A/q	H_2^+ (2)
Length	**mm**	**1378.69**
No. of cells		58
Transmission rate	%	97.27
Beam energy	keV	15 → 70
Input Trans. emit (rms, norm)	mm-mrad	0.3000
Trans. emittance (rms, norm)	mm-mrad	0.3427
Long. emittance (rms)	**keV-deg**	**40.24**
Vane voltage	kV	20.14
min. vane-tip aperture	mm	6.83
vane-tip curvature	mm	9.30
r_0, mid-cell aperture	mm	9.30
Octupole term		0.070

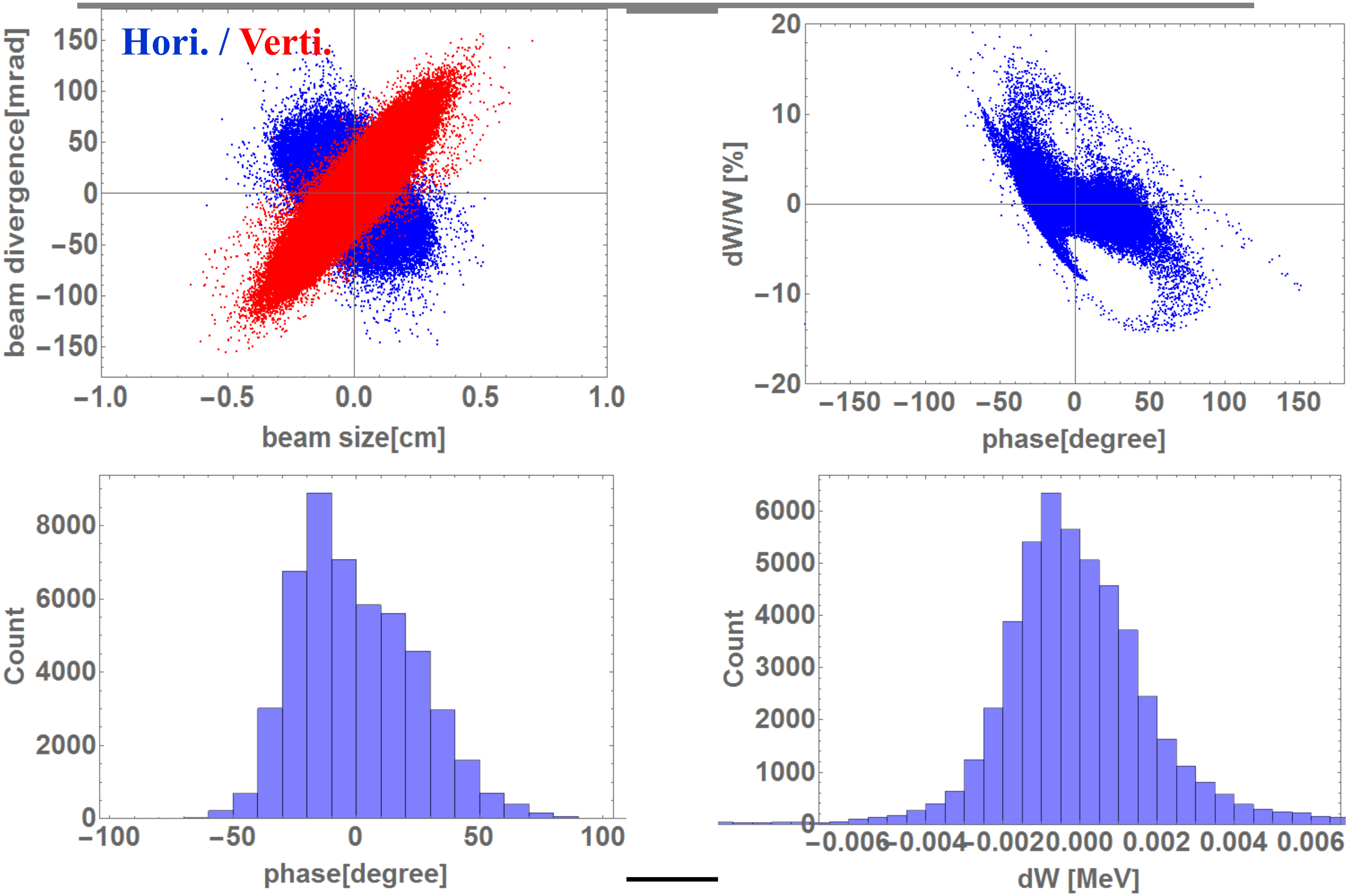
PARMTEQ-M code

Emittances in RFQ



	X	Y	Z
Emittance	**0.3430 μm-rad**	**0.3423 μm-rad**	**40.24 keV-deg**
α	0.5064	-1.9219	0.7990
β	4.2870 cm/rad	7.5528 cm/rad	14.7259 deg/keV

Beam distribution at the end of RFQ



Massachusetts Institute of Technology

KOREA UNIVERSITY

Considerations for the IsoDAR RFQ

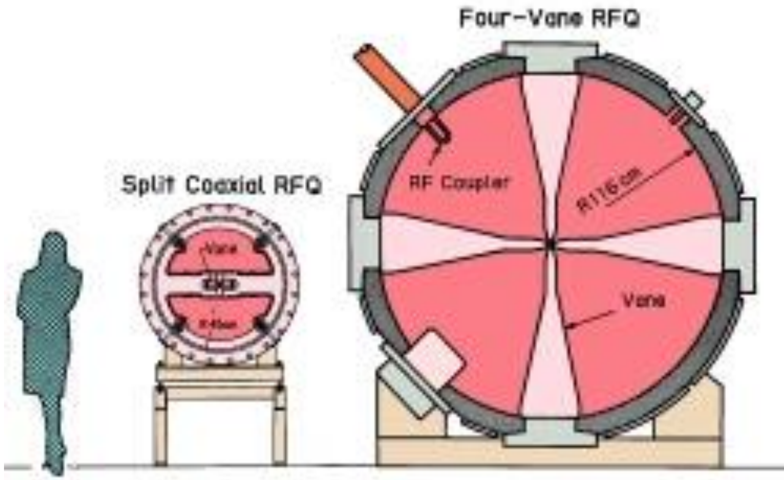
Parameters	Value	Unit
Particle (A/q)	H_2^+ (2)	

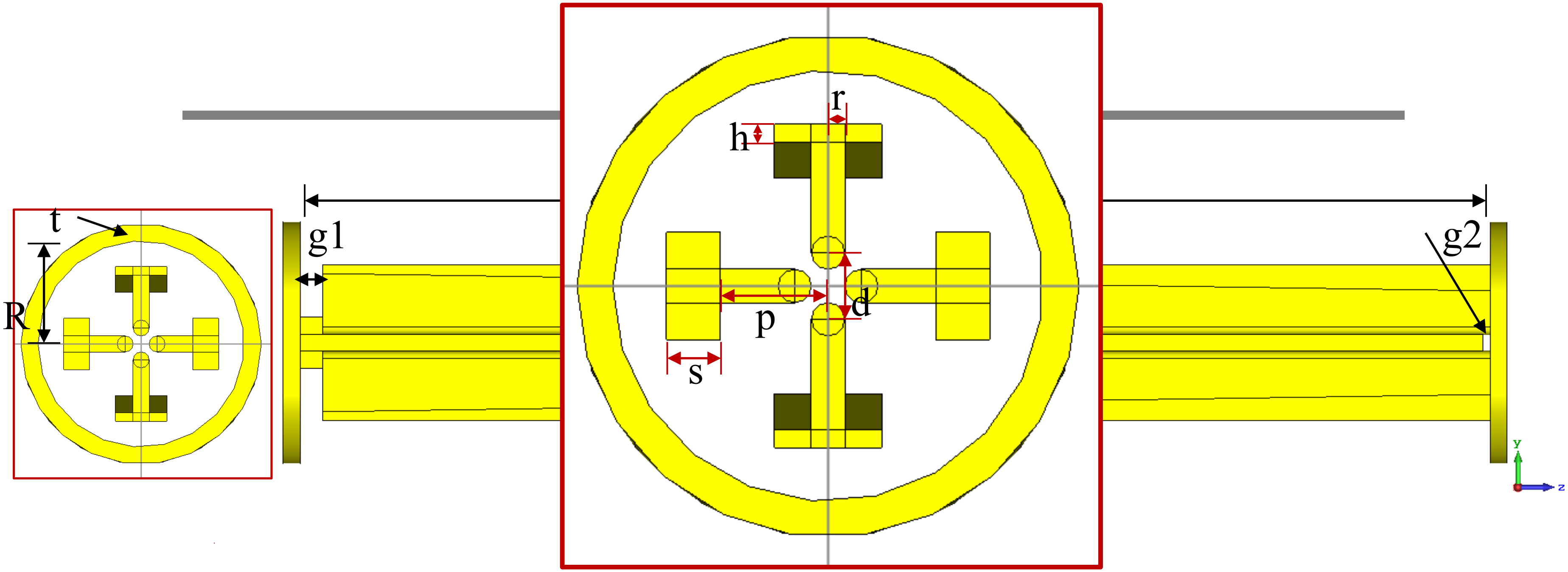
How to minimize transverse size of RFQ cavity?

Parameters	Value	Unit
Output beam energy	35	keV/u
Initial rms emittance	0.3	pi mm-mrad
Chamber diameter	**< 30**	**cm**
Longitudinal emittance	< 42	pi keV-deg
Length	< 150	cm

Split-coaxial RFQ

- Merit :
  - **Large inductance** compared with another structure $\omega \propto \frac{1}{\sqrt{LC}}$
  - Suitable for a low frequency RFQ.
- Demerit :
  - Long electrode are supported only at one point on the end-wall of the cavity
  - Difficult to install the vans directly.
- Solutions
  - Support each vane at points more than two
  - Called as multi-module cavity structure

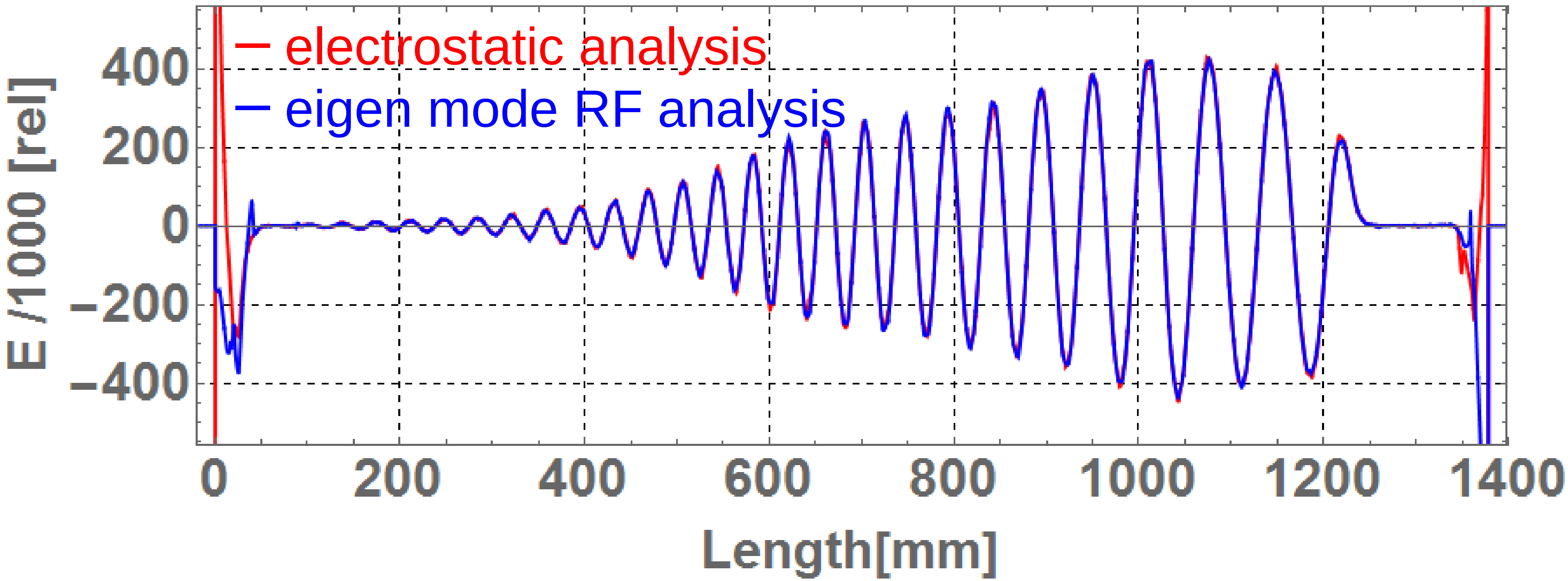




Elements	Values	Units	Elements	Values	Units
R, cavity radius	120	mm	l_1, horizontal vane length	1353.07	mm
r, electrode radius	9.30	mm	l_2, vertical vane length	1370.34	mm
d, electrode distance	37.2	mm	**L**, cavity length	**1378.69**	mm
$\mathbf{g_1}$, gap b.t.w h. vane and cavity	25.62	mm	**t**, cavity thickness	20	mm
$\mathbf{g_2}$, gap b.t.w v. vane and cavity	8.35	mm	**s**, vane skirt max thickness	30	mm
p, vane skirt position	60	mm	**h**, vane skirt min thickness	10	mm

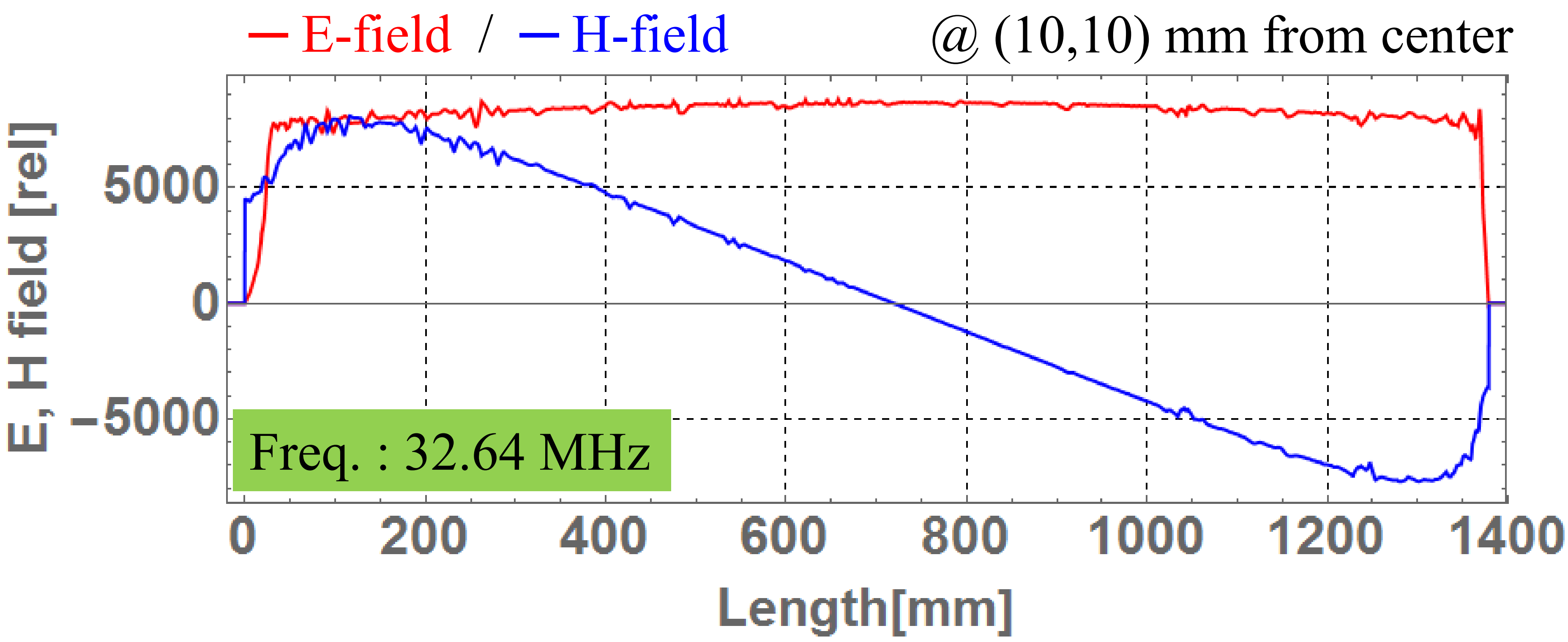
Split-Coaxial RFQ

- RF simulation result re-scaled as from 1.0 J to 0.165 J



✓ We obtained same field distributions from static and eigen mode analysis

EM field dist. in Split-Coaxial RFQ



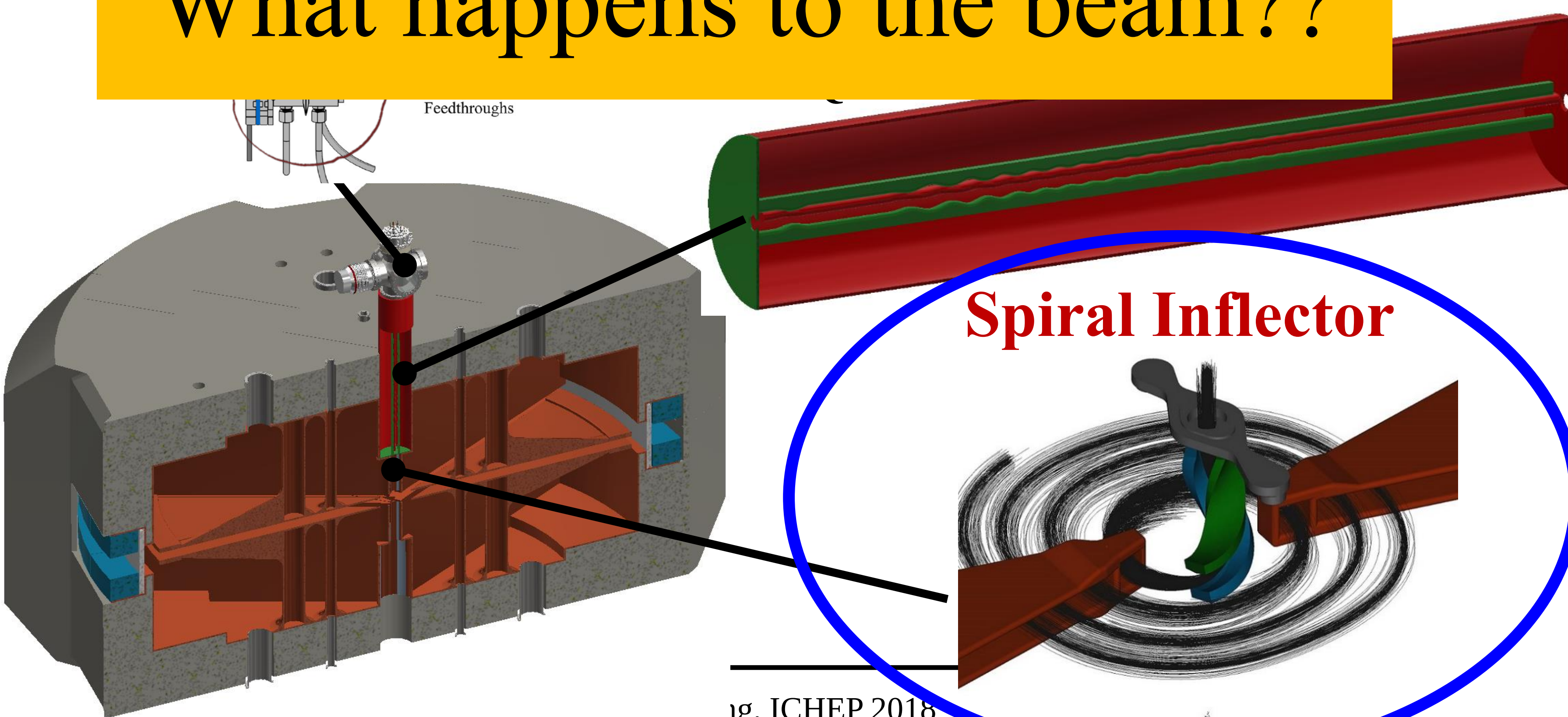
✓ The special magnetic field distributions give advantage of a small resonance frequency with small diameter of cavity.

Layout of the IsoDAR accelerator system

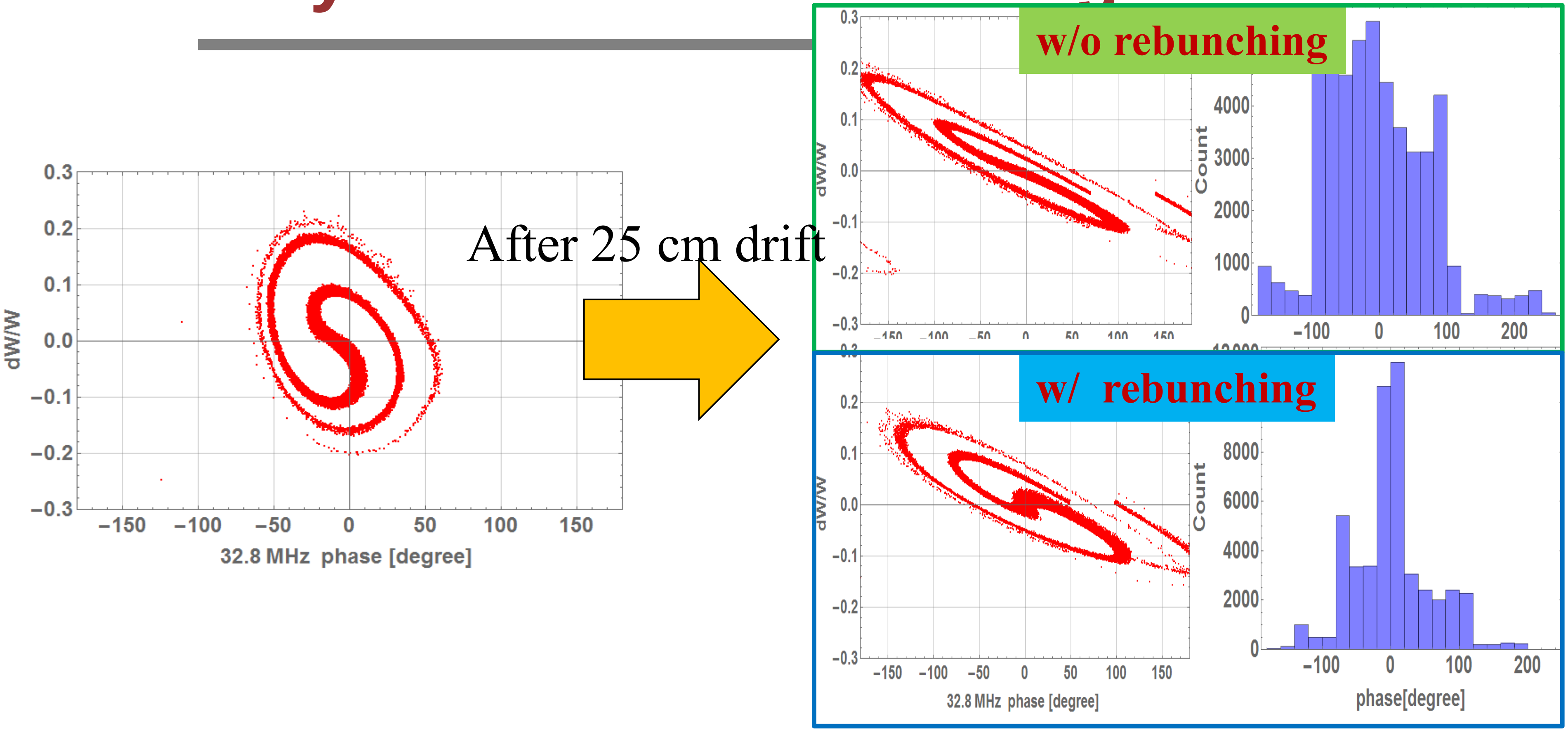
Ion source / LEBT

P)

After the exit of the RFQ, What happens to the beam??



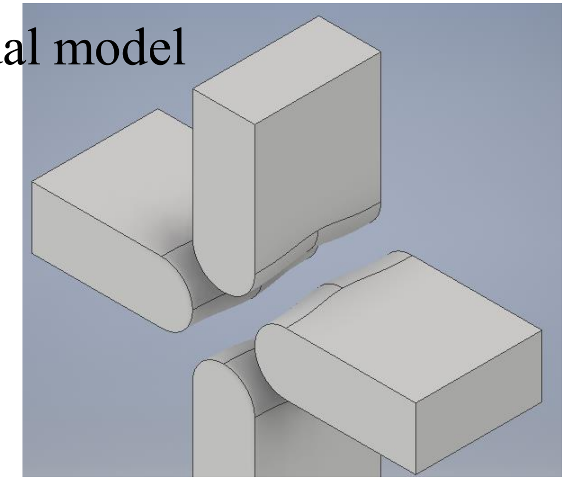
Why we need re-bunching



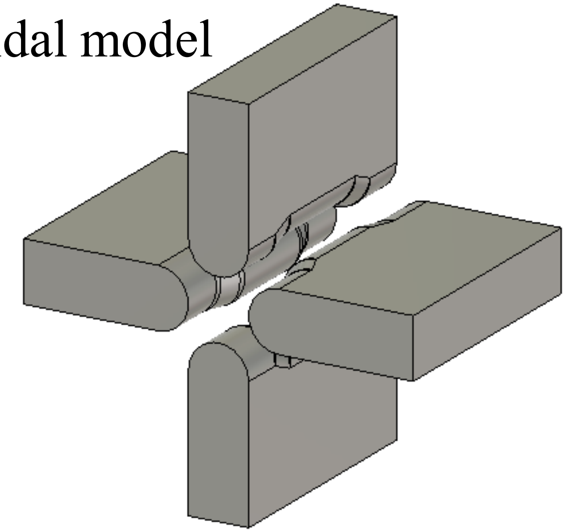
- ✓ Longitudinal phase distributions increase quickly right after exit of the RFQ.
- ✓ We don't want to install MEBT for focusing beam between RFQ and Cyclotron
- ➢ We try to add re-buncher cell in the transition cell of the RFQ.

Rebuncher design

Sinusoidal model



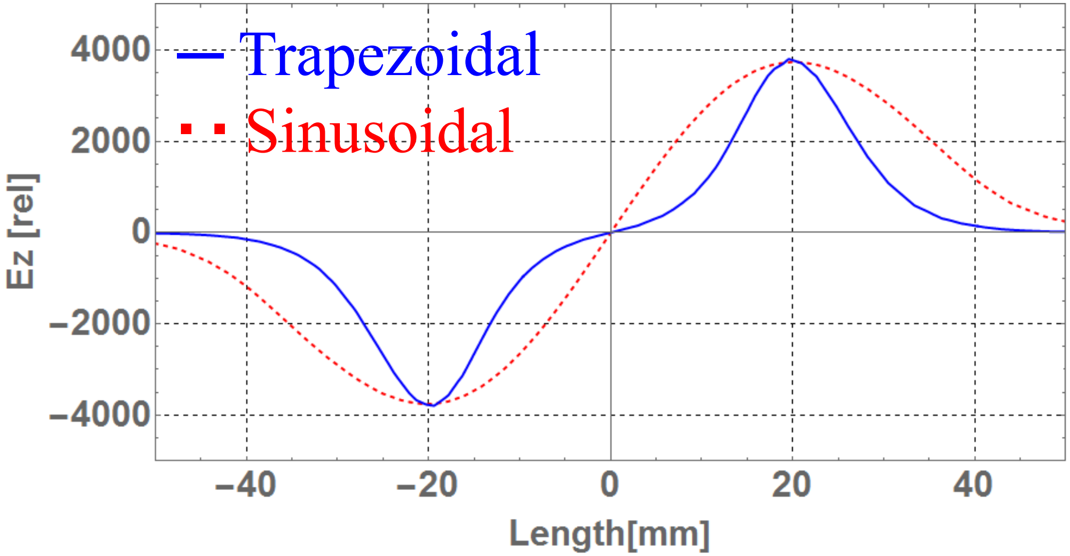
Trapezoidal model



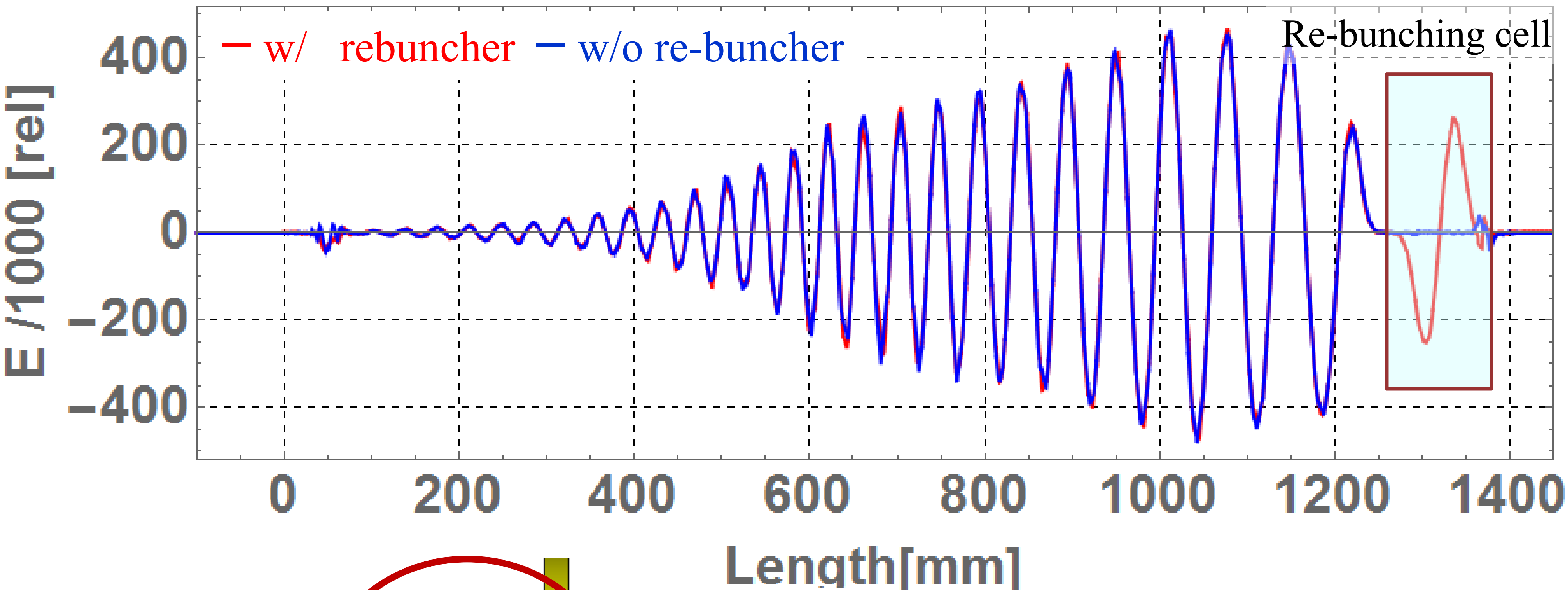
In order to separate RFQ and re-buncher field distributions, trapezoidal modeling employed.

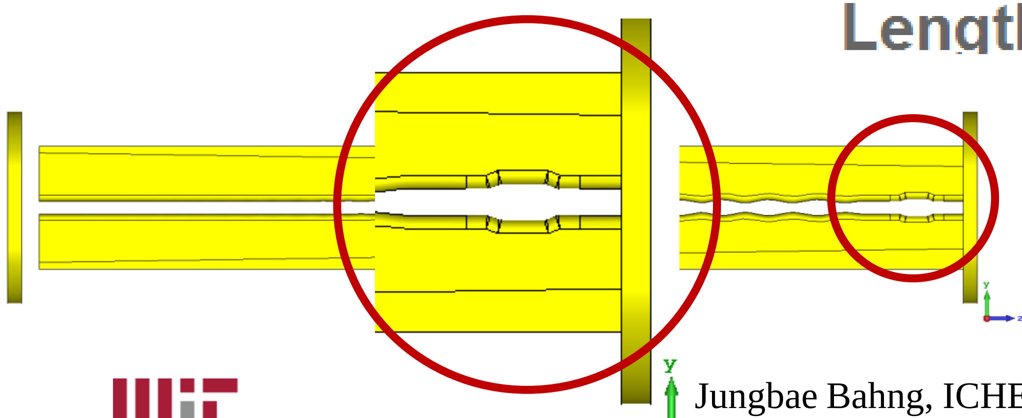
cell length : $\beta_{rel}\,\lambda_{free}$

$= 7.894$ cm



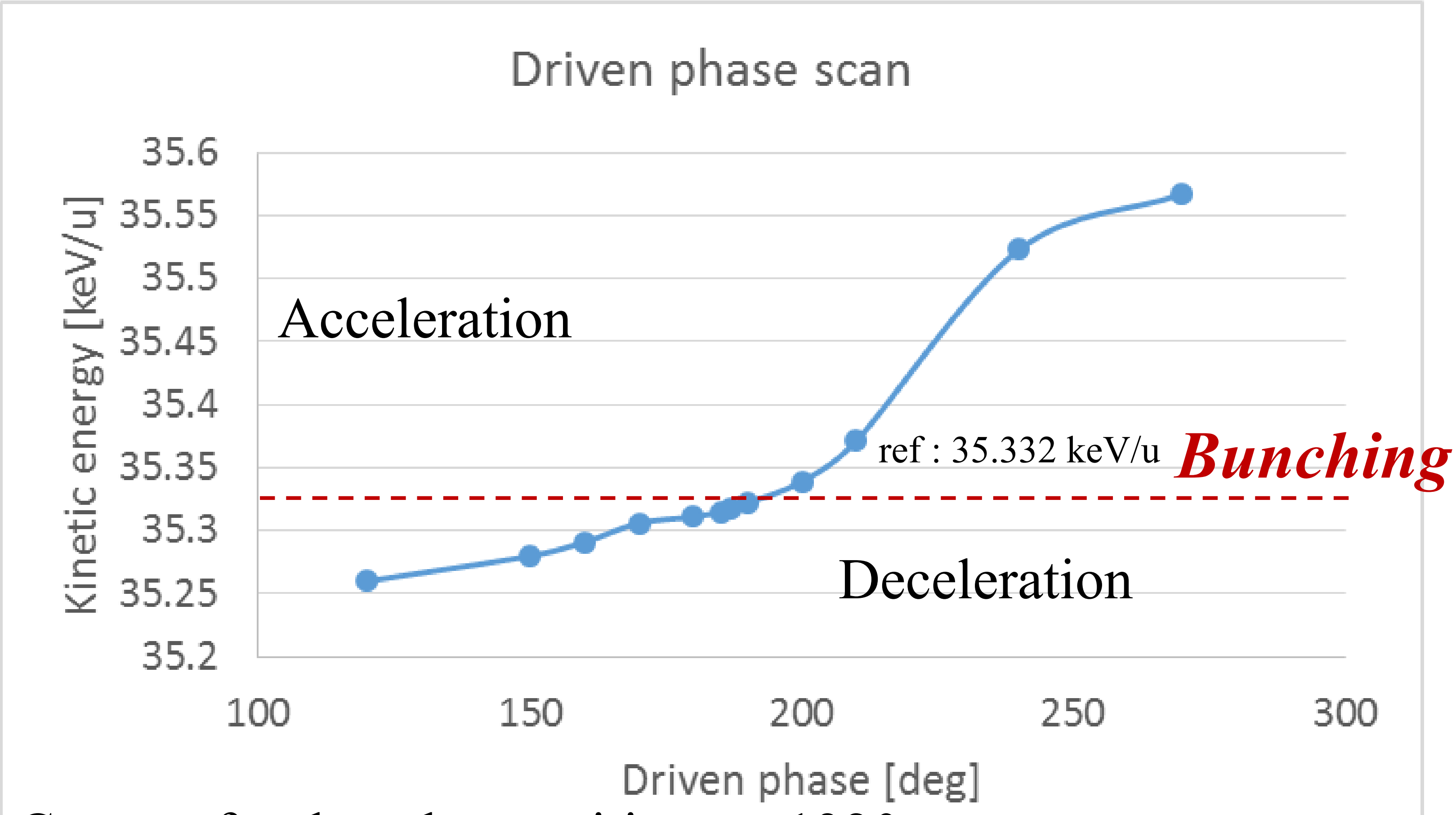
Electrostatic field distributions





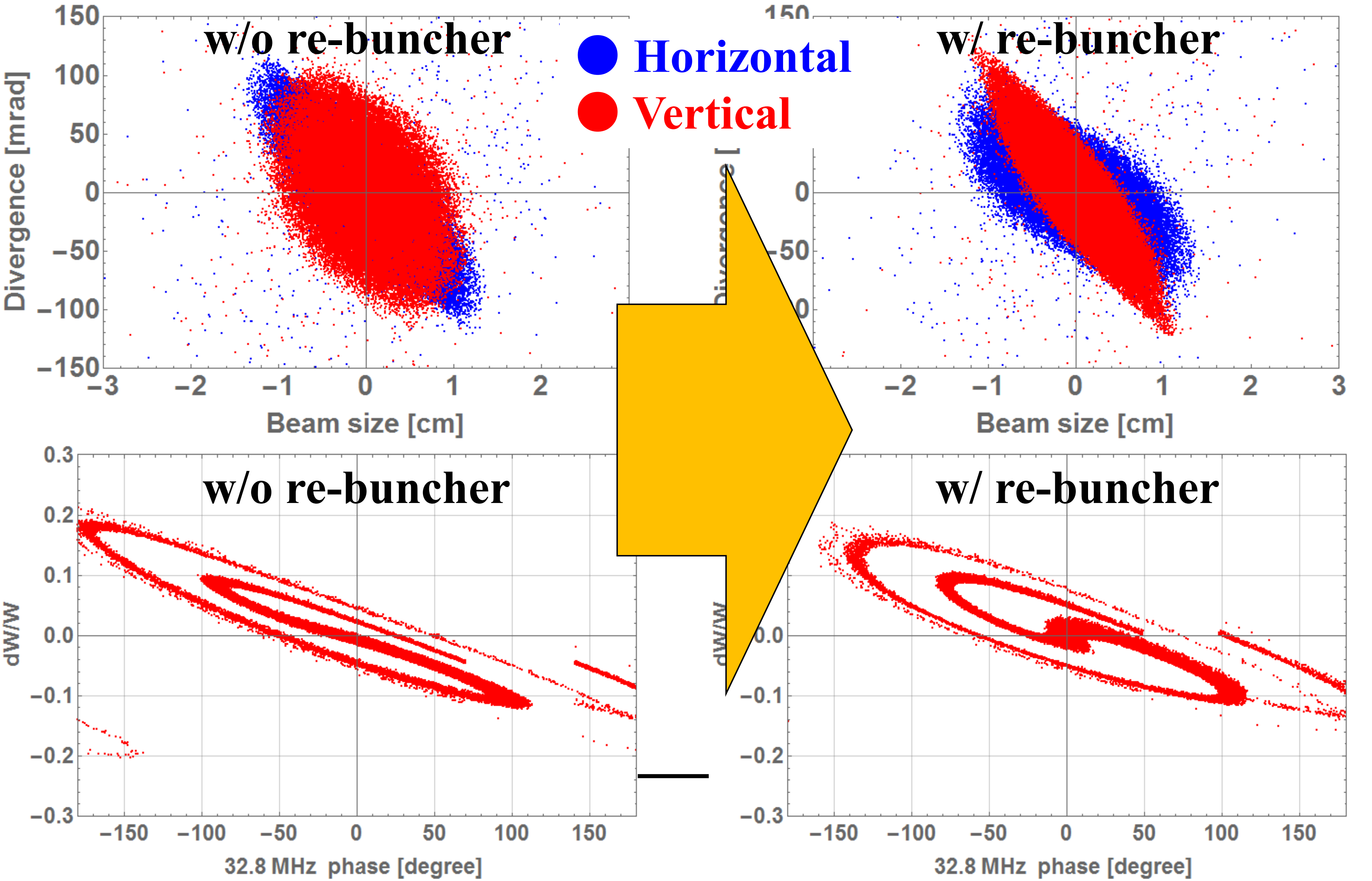
✓ Syn. phase to re-buncher could be controlled by changing position of re-buncher.

re-buncher position scan

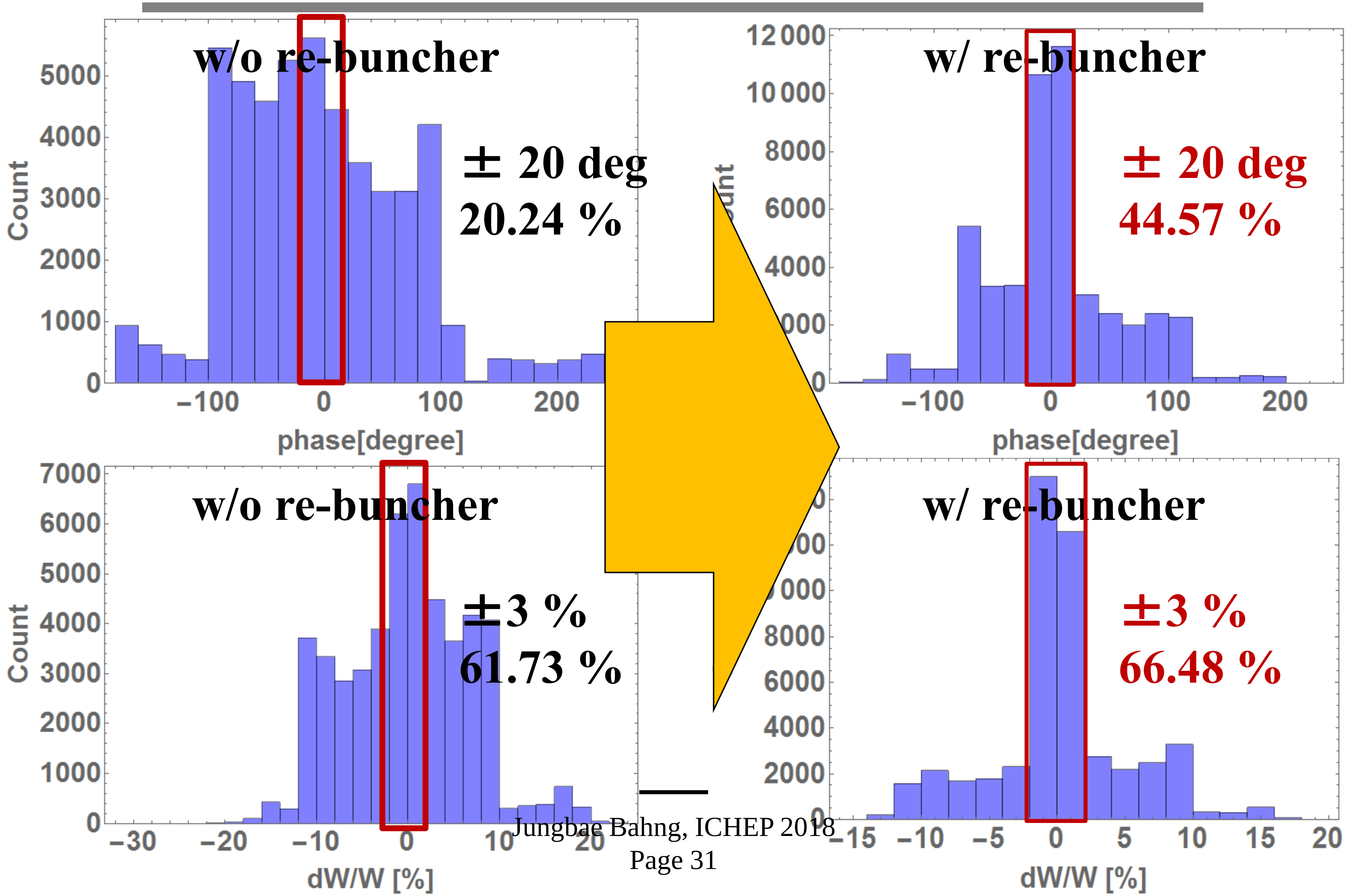


Center of re-buncher position : ~1320 mm

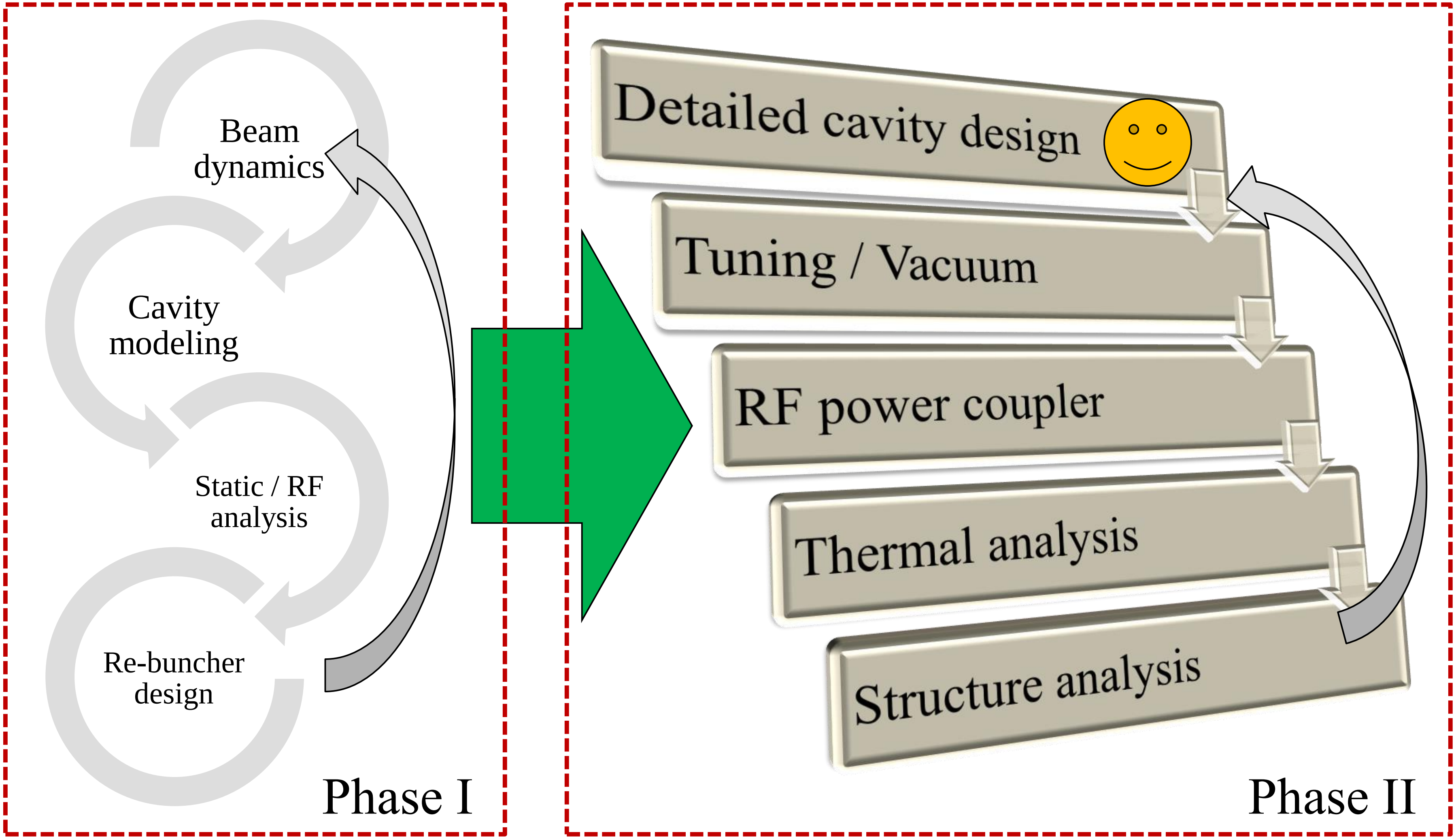
Beam dynamics with re-buncher



Beam dynamics with re-buncher



Next step


Beam dynamics
Cavity modeling
Static / RF analysis
Re-buncher design
Phase I
Detailed cavity design
Tuning / Vacuum
RF power coupler
Thermal analysis
Structure analysis
Phase II

Summary

- We have shown preliminary designs and simulations show achieving high efficient injection into the cyclotron.
- We designed RFQ has 40 keV-deg of tiny longitudinal emittance to be accepted in cyclotron with 1.4 meter long.
- By applying split-coaxial model, IsoDAR RFQ satisfies small diameter restriction as 24 cm at 32.8 MHz of operation frequency.
- To avoid longitudinal phase increment right after RFQ, re-buncher is added in the RFQ transition cell.
- Re-buncher employed trapezoidal shape to increase bunching efficiency and separate main RFQ field distribution.
- Start-to-End simulation from IS to cyclotron needed as next step.

Thank you for your attention!

Have a fun time in the Korea.