



# Studies On Superconducting Deuteron Driver Linac For BISOL

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19 June 2018



# Outline

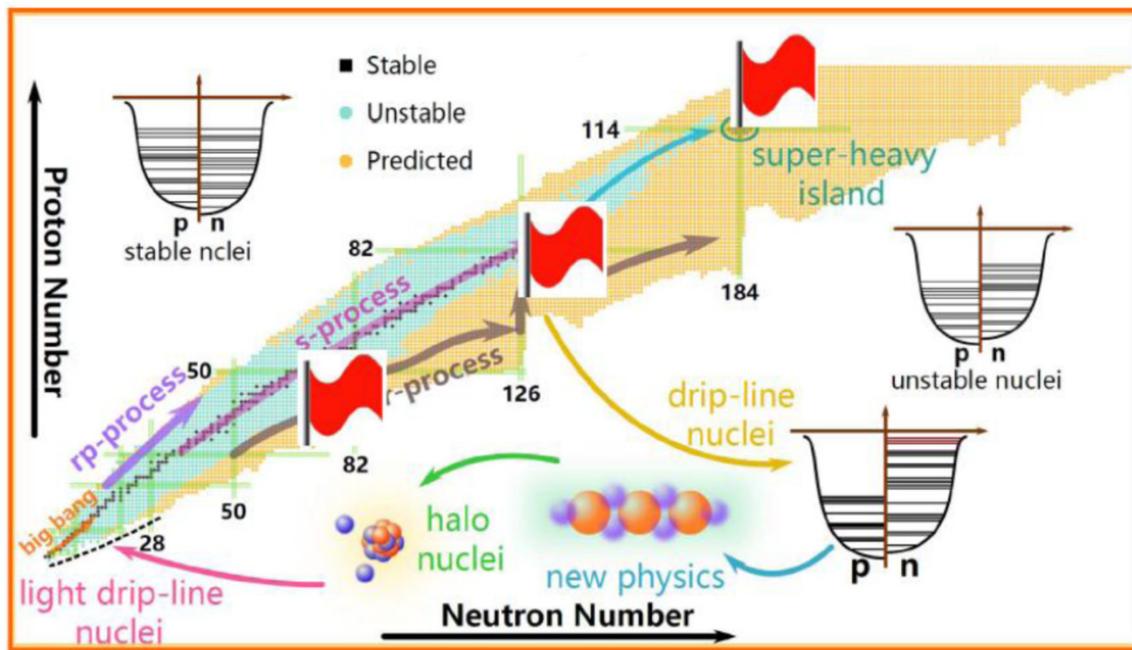
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- Introduction of BISOL deuteron accelerator
- Beam dynamic simulation of the deuteron accelerator
- HWR cavity performance for the deuteron accelerator
- Summary



# BISOL (Beijing-ISOL): Beijing Isotope-Separation-On-Line Neutron-Rich Beam Facility

— A facility to producing neutron rich rare isotope ions by means of ISOL+PF



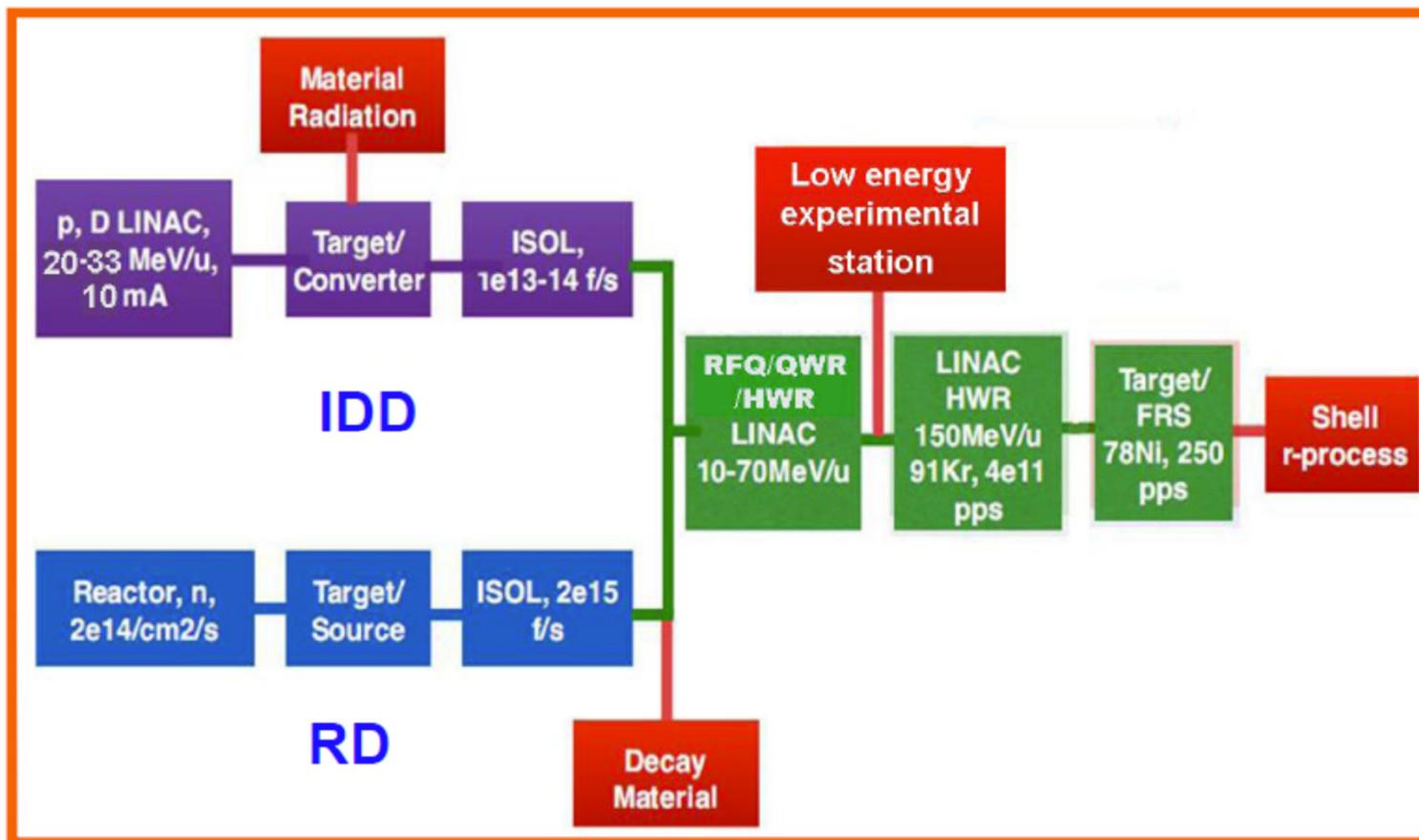
Great scientific questions at the expanded nuclear chart (3-flags)

- New physics at the drip-lines
- Nuclear-processes in creating heavy elements in the stars
- Ways towards the super-heavy stable island



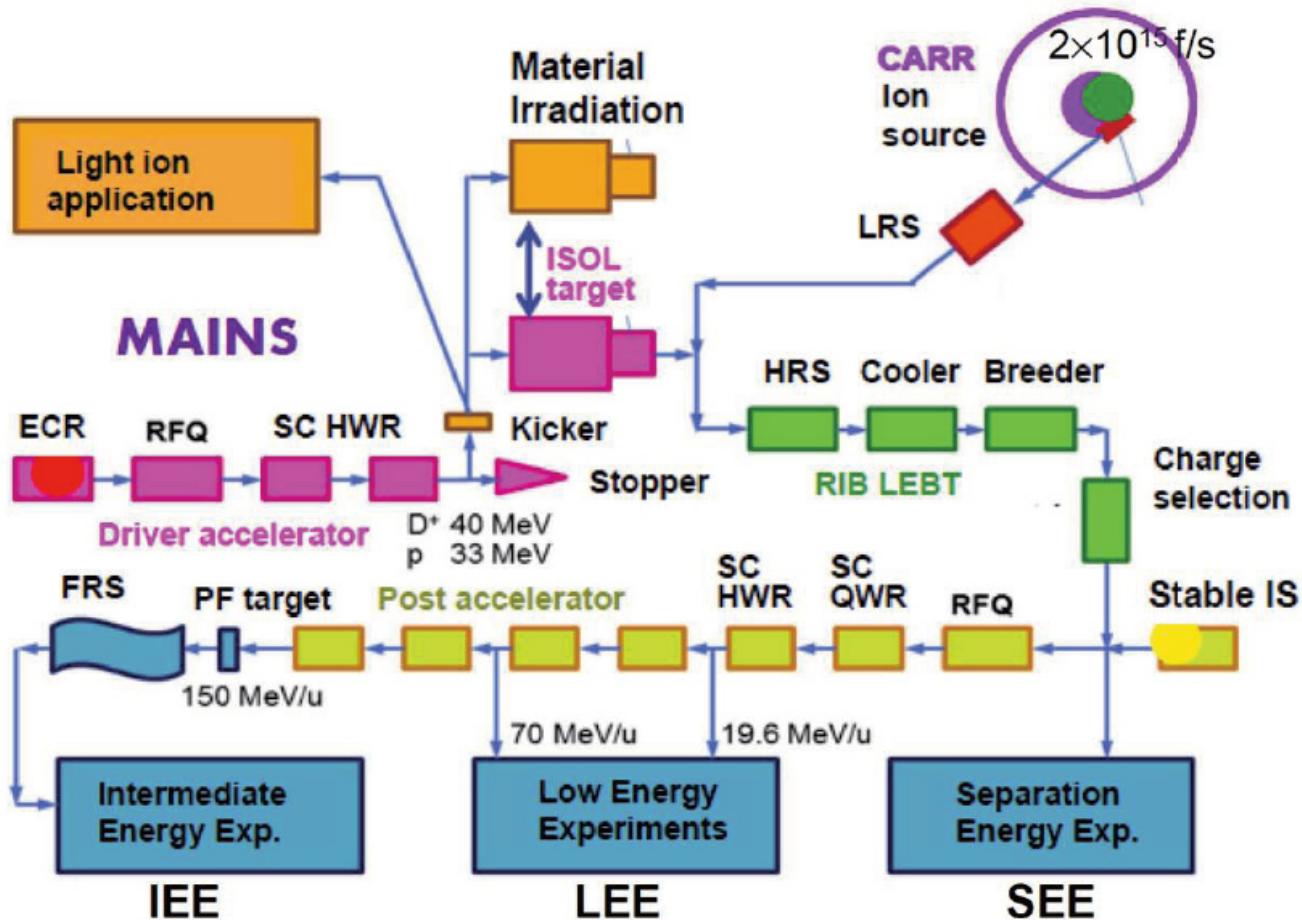
# Basic solutions provided by BISOL

- ◆ Reactor driver (RD) + intense deuteron-beam driver (IDD)
- ◆ Isotope separation on line (ISOL) + projectile fragmentation (PF)
- ◆ Basic science questions + key application questions





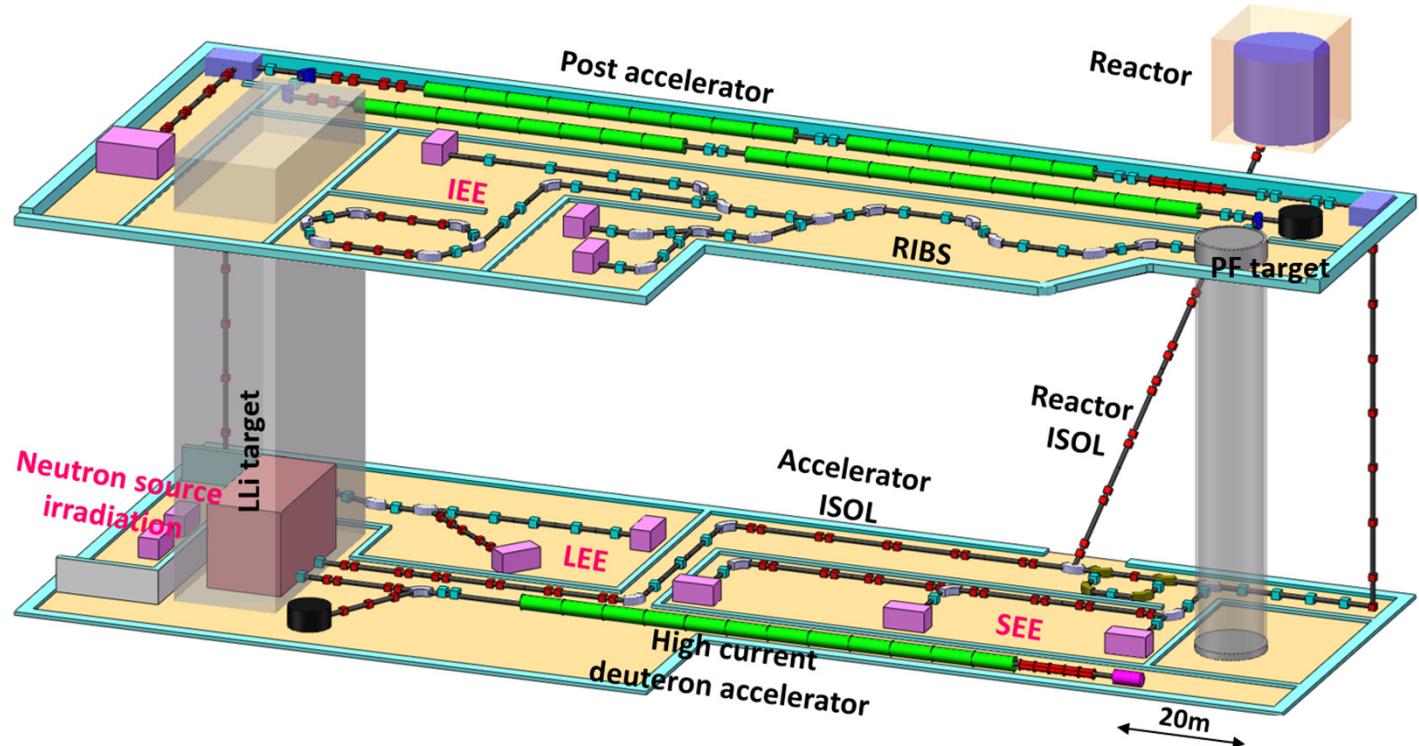
# Specifications of various parts of the BISOL



The site of BISOL will be located at CIAE in Beijing



# Schematic view of the arrangement of the BISOL facility



## 1) Double drivers

- ① CARR:  $8 \times 10^{14} \text{ n/cm}^2/\text{s}$ , 5 g  $^{235}\text{U}$ ;  $2 \times 10^{15} \text{ f/s}$
- ② D-LINAC: 40 MeV, ~10 mA, LLi target;  $5 \times 10^{14} \text{ n/cm}^2/\text{s}$

## 2) ISOL+PF

ISOL:  $m/\Delta m \sim 2000-20000$

SEE: Separation Energy Experiments ( $\sim 20\text{keV/q}$ )

Post-Acc: 20-150 MeV/u

PF separator: 7 Tm

LEE: LE Experiments

IEE: IE Experiments

## 3) Multiple-operation schemes

- ① CARR + ISOL + PA for RIB  
D-LINAC + LLi for n-beam
- ② D-LINAC + LLi + PA for RIB
- ③ D-LINAC + LLi for n-beam  
PA for stable beams

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# Major Milestones of BISOL

- In 2011: CIAE and PKU signed agreement to jointly promoting an ISOL-type RIB facility in Beijing area. As a result the previously proposed CARIF and ImPUF were merged into Beijing-ISOL.
- In Oct. 2012: An IAC was formed and a review meeting was held at PKU to evaluate the “Initial Conceptual Design of the BISOL” .
- In 2013, the advanced ISOL-type facility was adopted in “the national mid- and long-range plan ( till 2030) of the major facilities for science and technology development” .
- In May-June 2016, proposed large-scale science facilities (more than 50 proposals for all fields) were reviewed by the National development and Reform Council. BISOL was successfully classed into the list of the preparation facilities (10+5 facilities in total).
- In Dec. 2016, the government has officially announced the results for the 13th 5-year plan.
- In Mar. 2017, the 1st BISOL user meeting was held at PKU, with ~ 150 participants and very active discussions.
- In Jun. 2017, BISOL-CD-1 was finalized and evaluated by an domestic expert committee, being ready for the next national review and the next IAC review.



# Layout of the Deuteron Accelerator

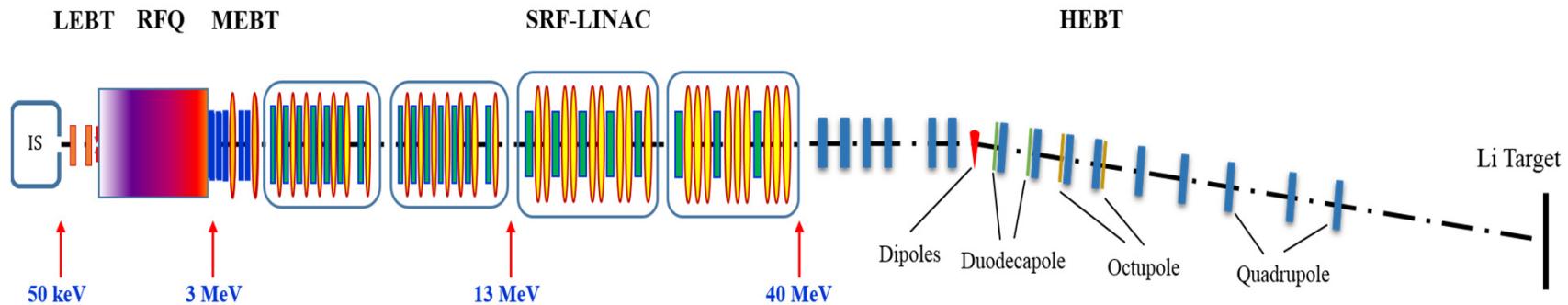


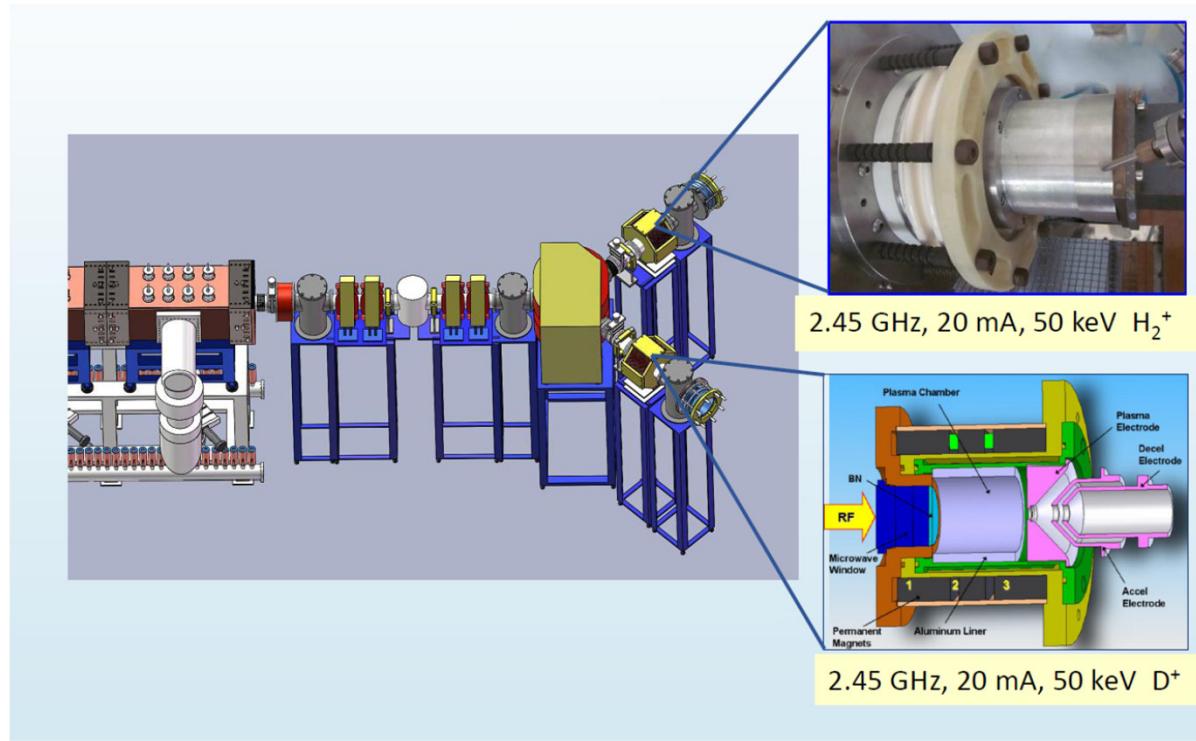
Table Design parameters of the deuteron linac

Particles	Deuteron	
Energy	40	MeV
Current (Phase I)	10	mA
Beam power	400	kW
rf frequency	162.5	MHz
Duty factor	100	%
Beam loss	<1	W/m
Neutron flux	$5 \times 10^{14}$	n/cm <sup>2</sup> /s



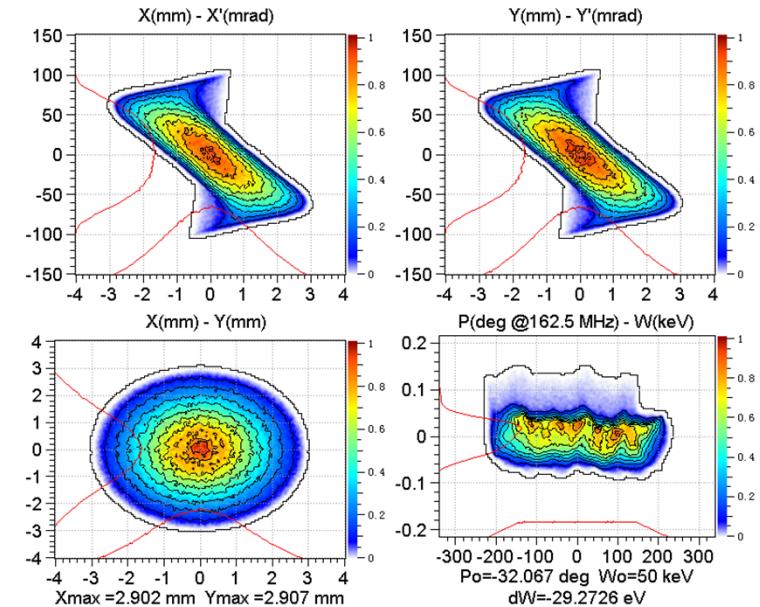
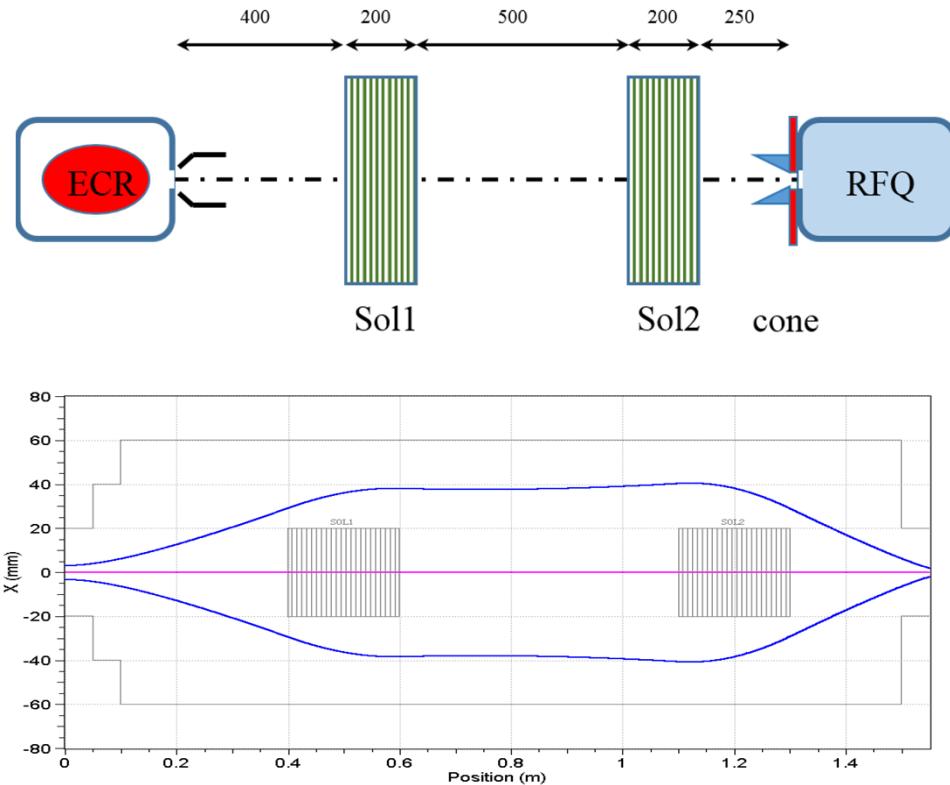
# Beam dynamic simulation of the deuteron accelerator

# Ion Sources at PKU



- For commissioning of accelerator instead of D<sup>+</sup>
- Providing H<sub>2</sub><sup>+</sup> beam for experiment terminal;
- As a redundancy of D<sup>+</sup> source

- ❖ PKU PMECRIS
- ❖ 120 mA H<sup>+</sup>
- ❖ 83 mA D<sup>+</sup>



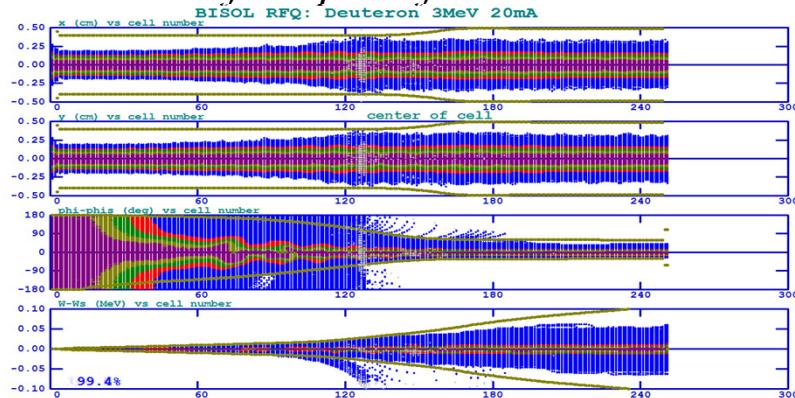
- 2 identical solenoids whose effective pole length is 200 mm.
- 2 steerers, BPMs.
- Solenoids magnetic field: 0.35T & 0.41 T, aperture 120 mm.
- The total length of beam line: 1.55 m
- diagnostic instruments: ACCT, FC, emittance meter

- ECR-IS extraction:  
 $\varepsilon_n = 0.17 \text{ mm}\cdot\text{mrad}$
- RFQ entrance:  
 $\varepsilon_n = 0.195 \text{ mm}\cdot\text{mrad}$ ,  
 $\alpha = 1.33$  and  $\beta = 0.042 \text{ mm/mrad}$   
Match to RFQ

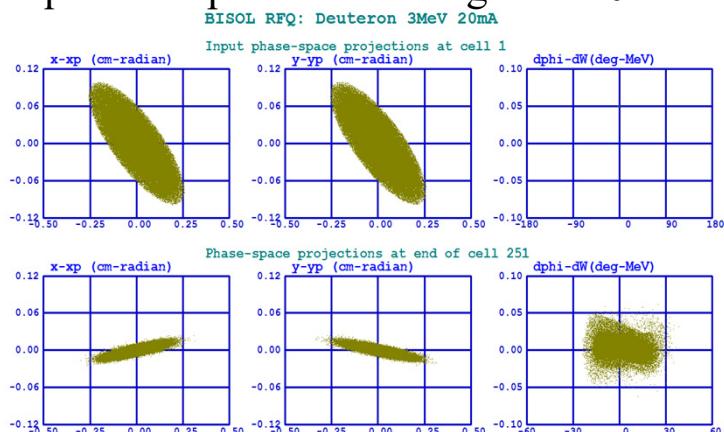
# RFQ designed for BISOL 1<sup>st</sup> stage

Design strategy:

- High beam transmission
- Low rf power dissipation
- Low surface peak field



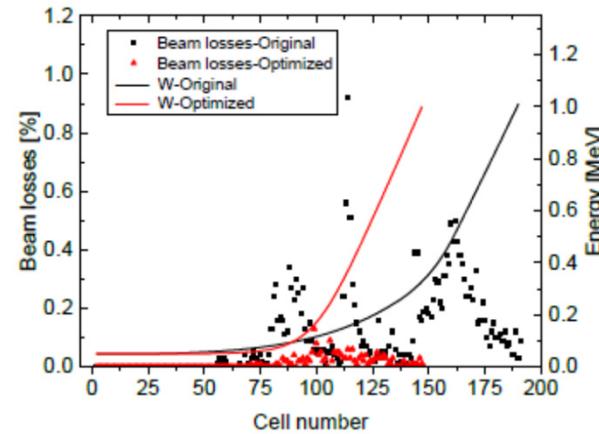
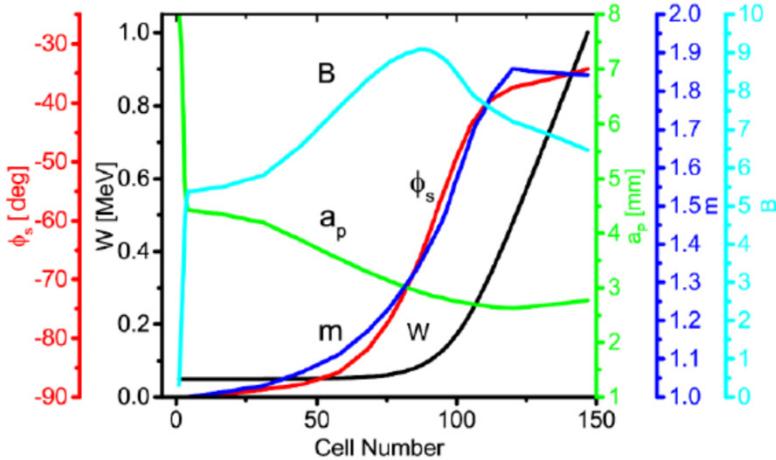
ParmteqM multi-particle tracking with  $10^5$  macro-particles



- High beam quality at the RFQ exit
- Short RFQ length

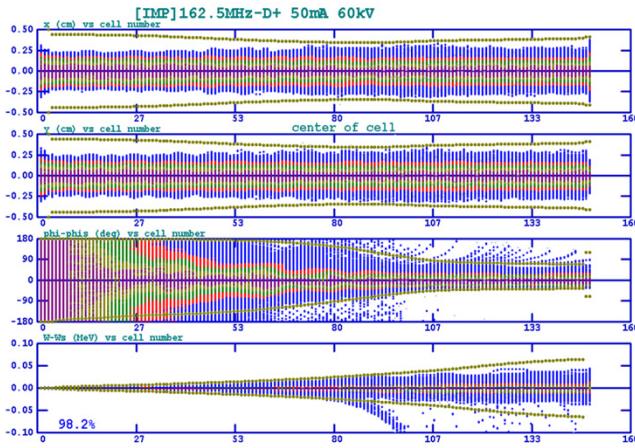
Parameter	Value	Unit
Particle	D <sup>+</sup>	
Frequency	162.5	MHz
Input energy	50	keV
Output energy	3.0	MeV
Beam Current	20	mA
Inter-vane voltage min/max	60/75	kV
Vane length	5.03	m
Maximum peak surface electric field	19.87	MV/m
Kilpatrick coefficient	1.46	
Minimum aperture radius	3.05	mm
Average aperture min/max	3.94/5.09	mm
Synchronous phase	-90 ~ -30	deg
Max. modulation factor	1.90	
Trans. input normalized rms emit.	0.20	mm·mrad
Trans. output normalized rms emit.	0.21	mm·mrad
Long. output rms emittance	0.09	
Transmission ratio (PARMTEQM) (W <sub>limit</sub> = 0.08 MeV)	99.41	%
Transmission ratio (Toutatis)	99.68	%
Accelerator ratio (Toutatis)	99.44	%

# 50mA D<sup>+</sup> prototype RFQ



Beam loss along the axis

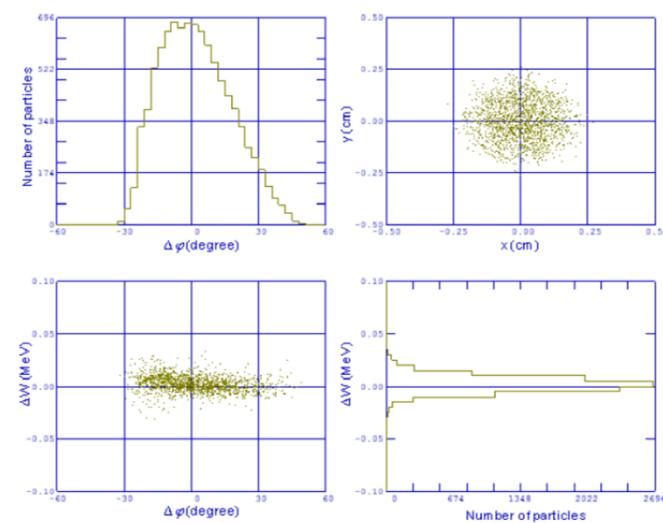
Parameters along the axis



Transport efficiency

•2018/6/19

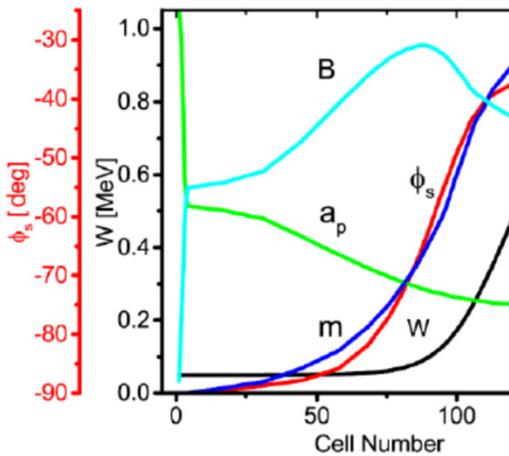
HB2018, Daejeon, South Korea



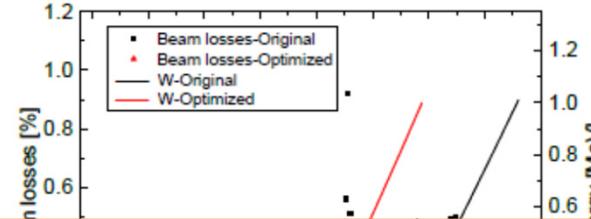
Beam distribution at exit of RFQ

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# 50mA D<sup>+</sup> prototype RFQ



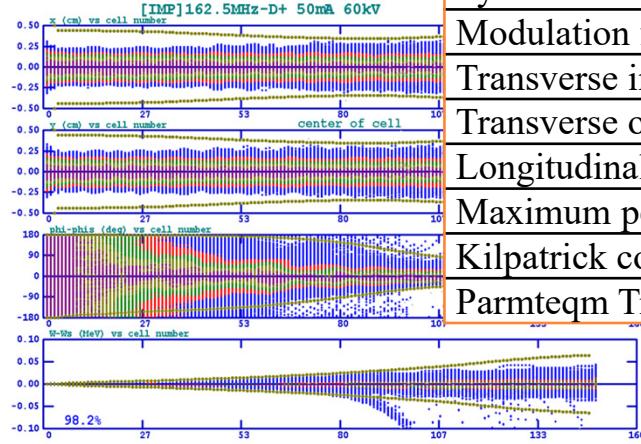
Parameters along the cell number



axis

Parameters along the cell number

Parameters	Value
Intervane voltage [kV]	60
Input energy [MeV]	0.05
Output energy [MeV]	1.01
Minimum aperture radius [cm]	0.263
Aperture [cm]	0.388
Cavity length [m]	1.81
Synchronous phase [Deg.]	-90 ~ -34
Modulation factor	1 ~ 1.86
Transverse input emittance [ $\pi$ mm mrad]	0.20
Transverse output emittance [ $\pi$ mm mrad]	0.22
Longitudinal output emittance [MeV deg]	0.12
Maximum peak surface electric field [MV/m]	22.74
Kilpatrick coefficient	<b>1.67</b>
Parmeqm Transmission [%]	<b>98.2</b>

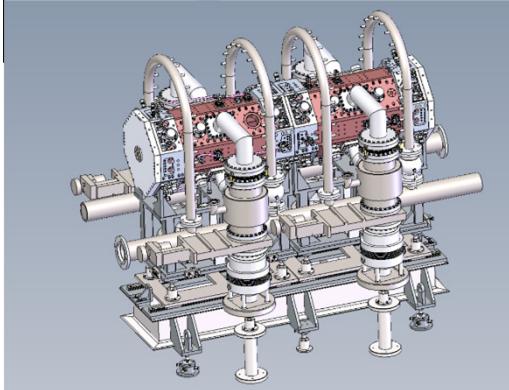


Transport efficiency

Beam distribution at exit of RFQ

# 50mA D<sup>+</sup> RFQ

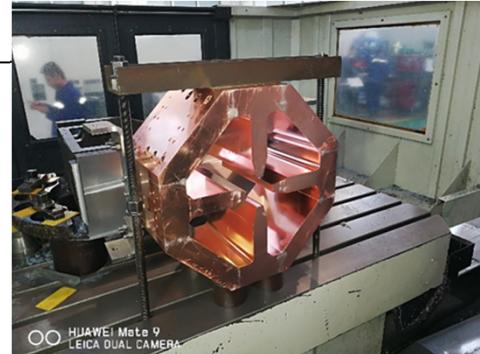
## Design and fabrication



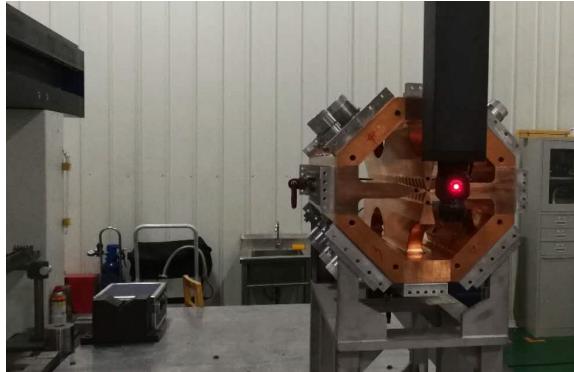
3D mechanical drawing



Ready for high power test  
and beam experiment



Experiment section for welding



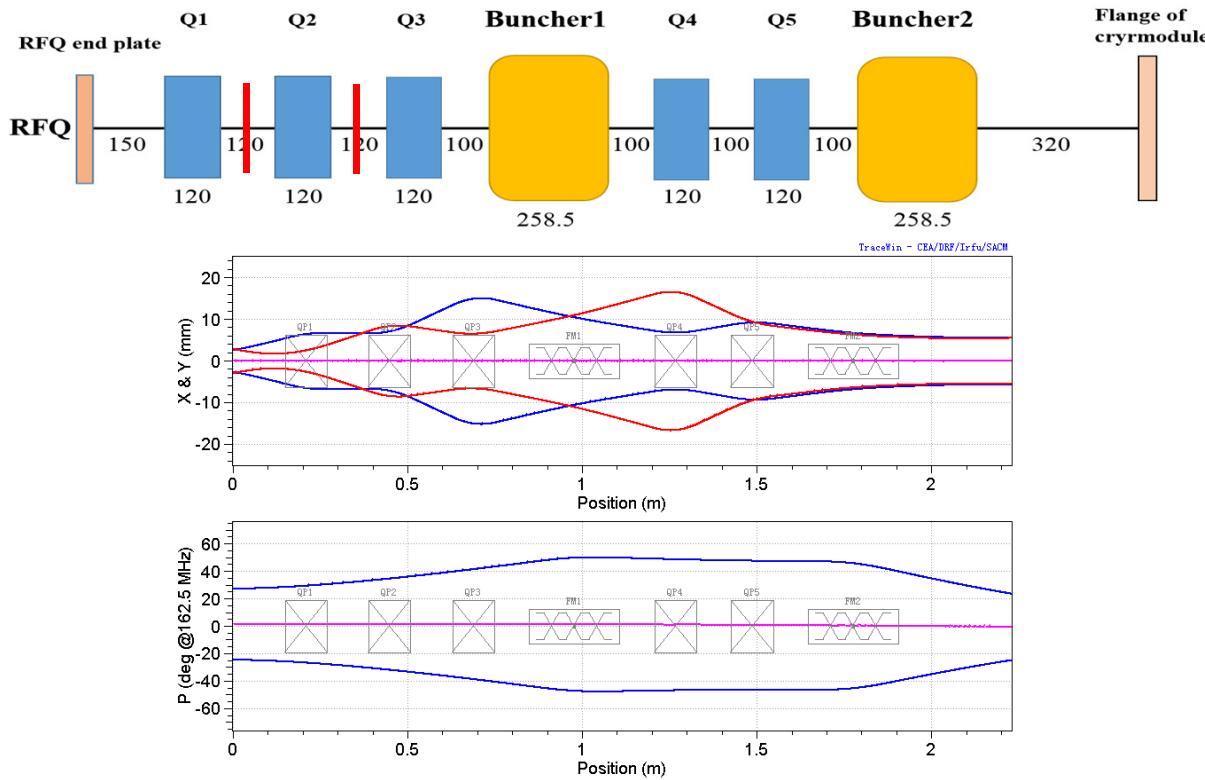
Three-coordinate measure



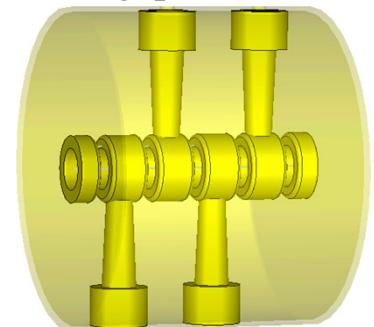
Vacuum brazing



# MEBT



five gaps IH buncher

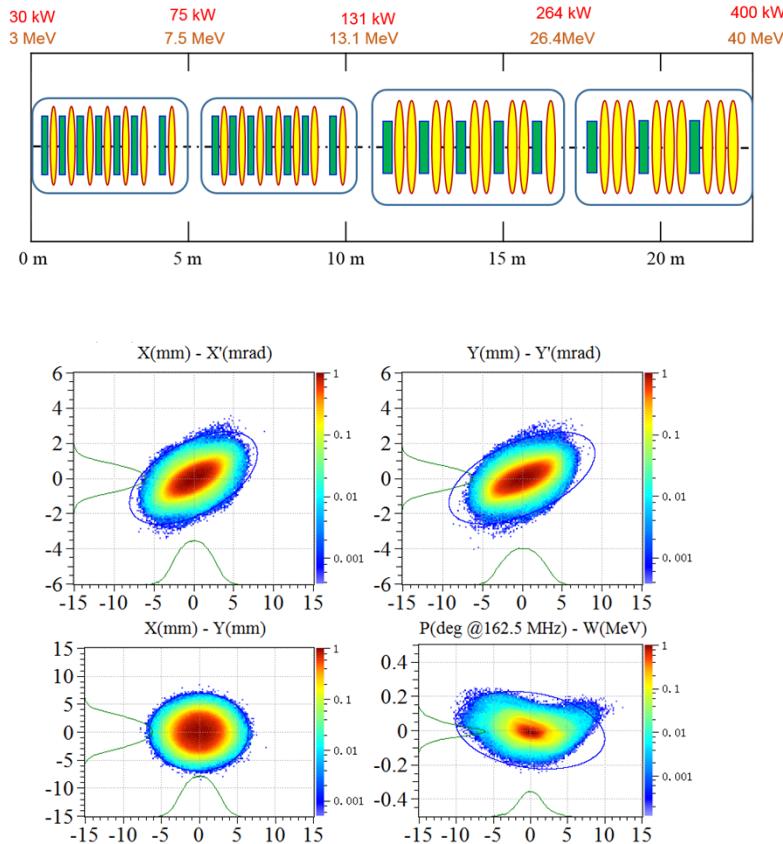


Element	Value
Cavity diameter (mm)	370
Aperture diameter (mm)	44
Cavity length (mm)	320
Q value	12000
Power (kW)	1.9
Mode separation (MHz)	162.3

- 5 quadrupoles and 2 bunchers to match beam in transverse (x, y) and longitudinal (z).
- 2 scrapers: clean out-of-energy particle and beam halo particles
- beam diagnose instruments and others: ACCT, FCT, BLOM
- BPMs, steerers: integrate to quadrupole package.



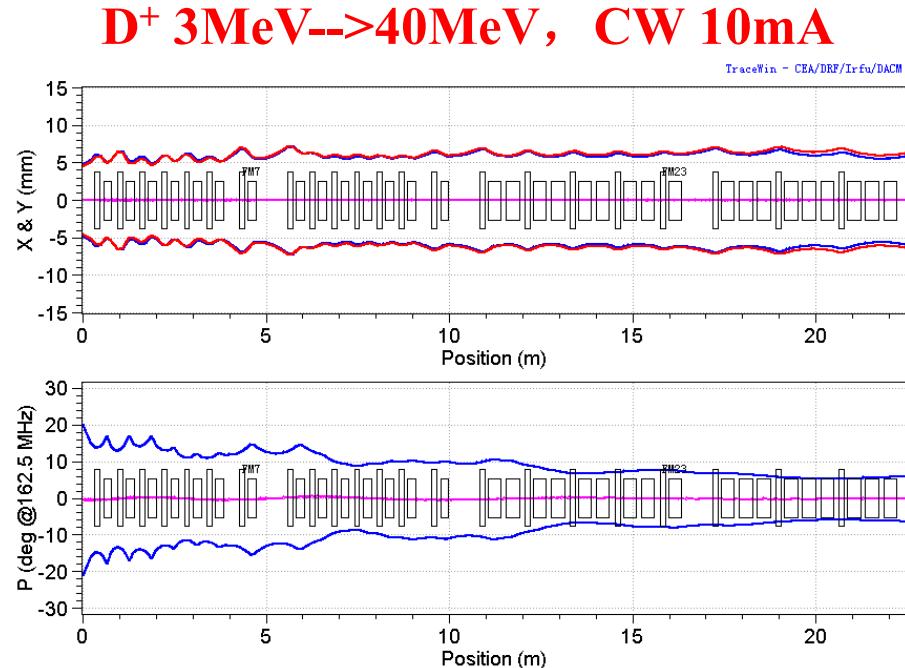
# beam dynamic simulation of SRF HWR010 and HWR016 cavities



Particle phase space distribution at the exit of the SRF linac

•2018/6/19

HB2018, Daejeon, South Korea

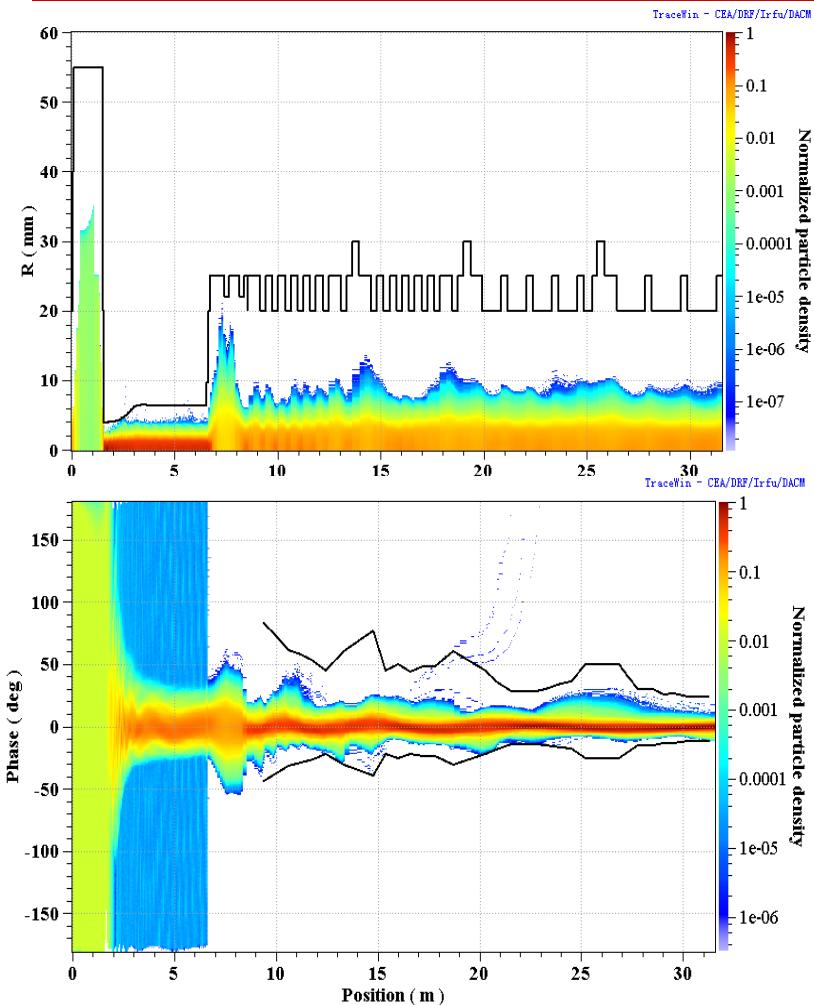


Envelope of deuteron beam along the SCL.  
Top: transverse envelope, x in blue and y in red.  
Bottom: longitudinal envelope.

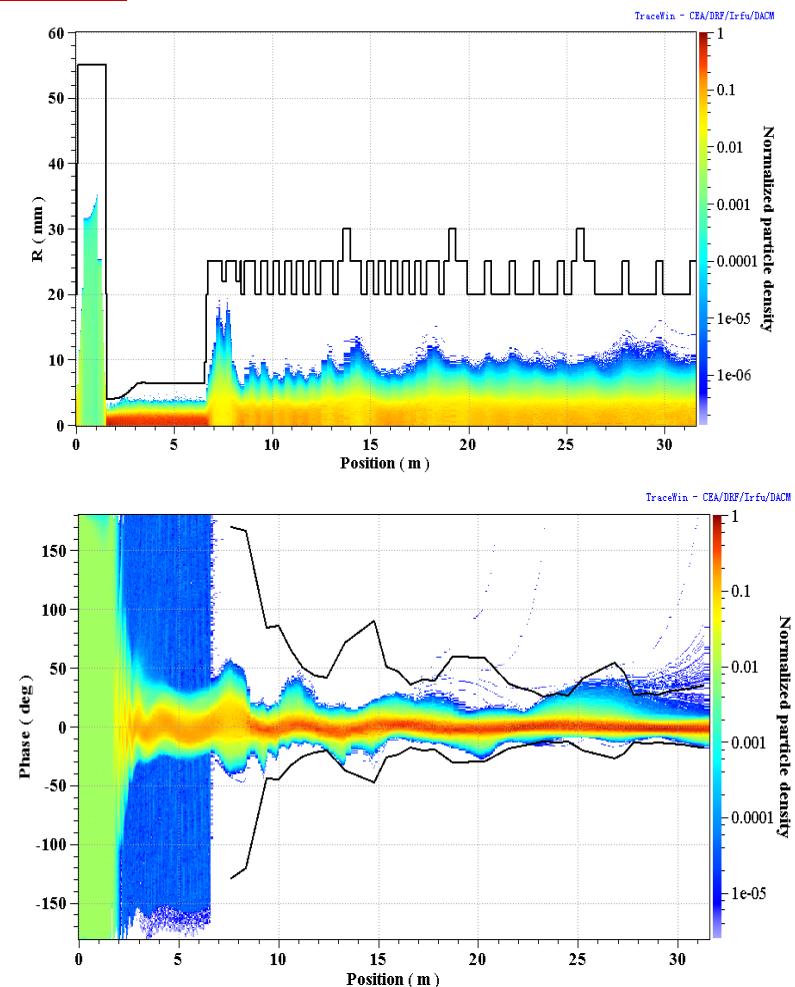
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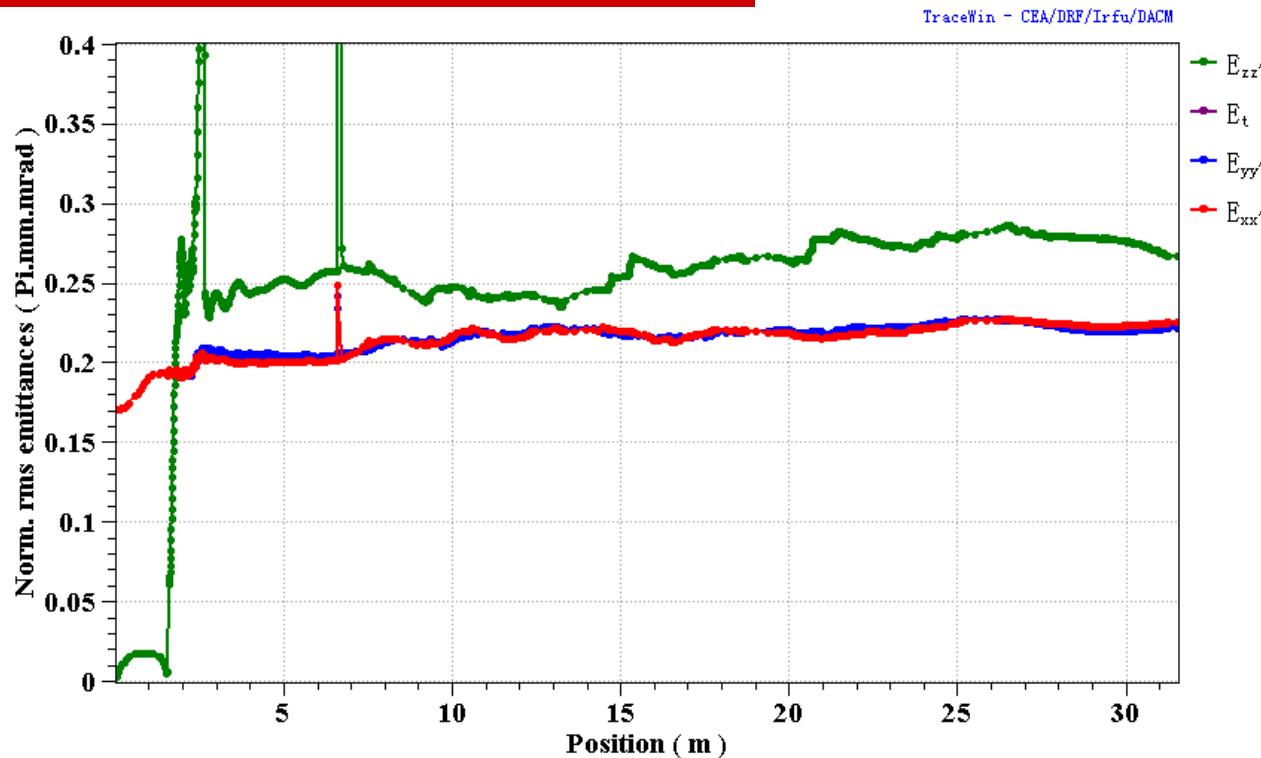
# Beam density from start to end



Beam density in transverse (top) and longitudinal (bottom) from start to end.



Beam density in transverse (top) and longitudinal (bottom) from start to end with errors.



Normalized rms emittance along the BISOL deuteron driver linac

The normalized rms transverse emittances of the output beam at the exit of the SRF linac:  $\varepsilon_x = 0.23 \text{ mm}\cdot\text{mrad}$ ,  $\varepsilon_y = 0.22 \text{ mm}\cdot\text{mrad}$ ,  $\varepsilon_z = 0.26 \text{ mm}\cdot\text{mrad}$ .

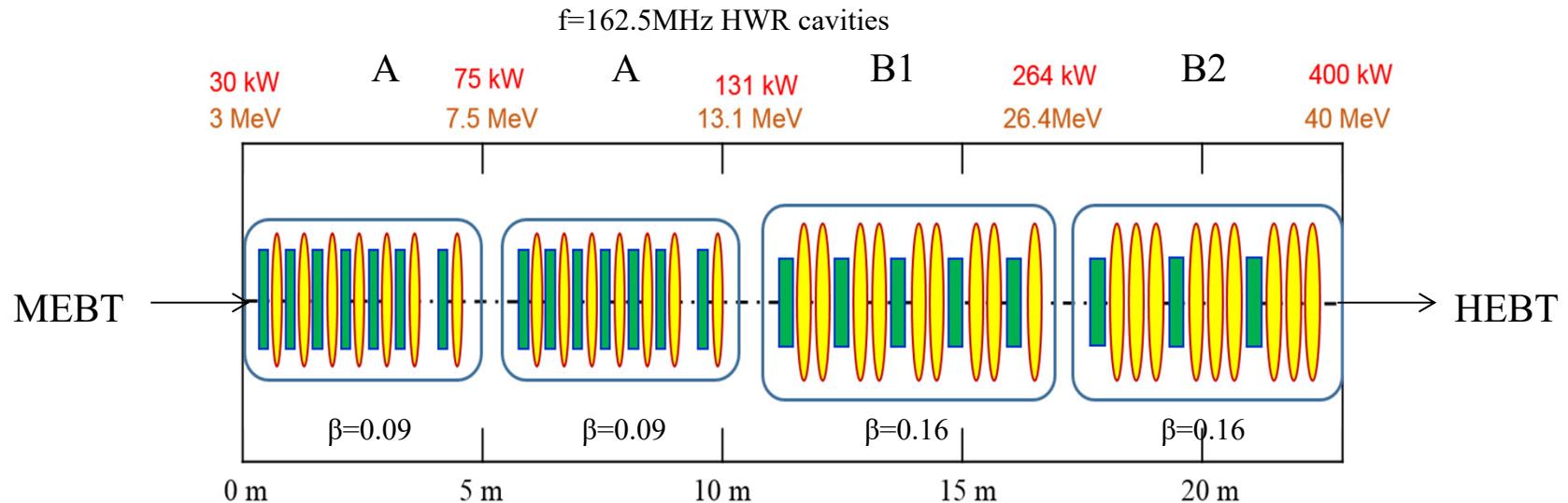
The emittance growths through the SRF-linac are 5% and 2% in the transverse and longitudinal planes.



# HWR cavity performance



# SRF Linac of the Deuteron Accelerator



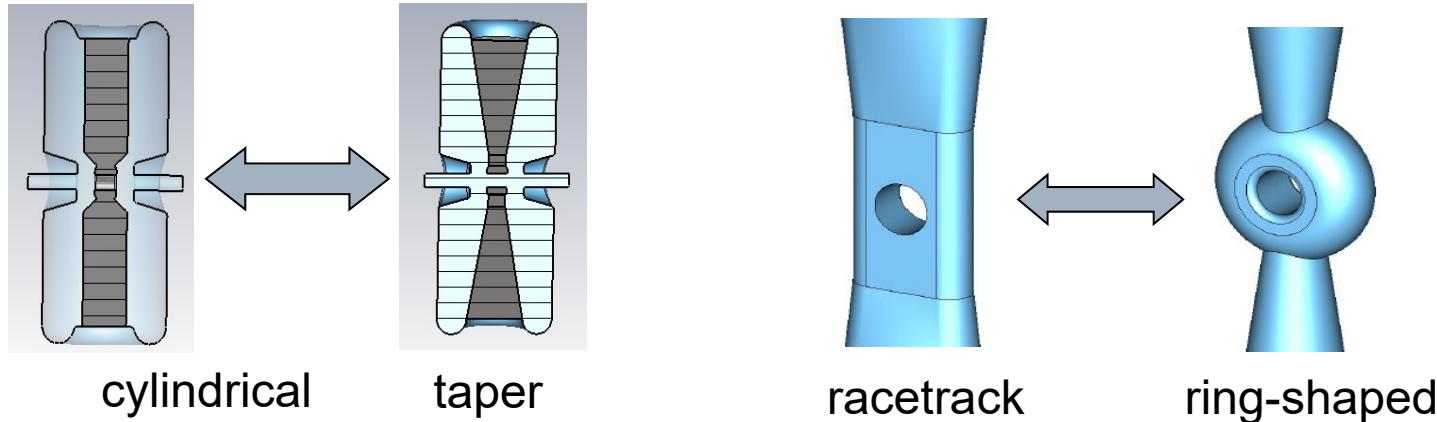
	<b>module A</b>	<b>module B1</b>	<b>module B2</b>
Module numbers	2	1	1
Cavity type	$\beta_g=0.09$ HWR	$\beta_g=0.16$ HWR	$\beta_g=0.16$ HWR
Caivities /module	7	9	9
Solenoids/module	7	5	3
Injection energy for D <sup>+</sup> (MeV)	3	13.1	26.4
Output energy for D+ (MeV)	13.1	26.4	40



# Cavity design

- At the first stage, the current of BISOL D accelerator is 10 mA at CW mode. In the future, the current will be upgraded to 50 mA for CW deuteron beam.
- The HWR cavities were designed to accelerate CW 50mA deuteron beams.

inner conductor design



- **increase shunt impedance**
- **decrease peak surface fields**
- **improve the mechanical properties**

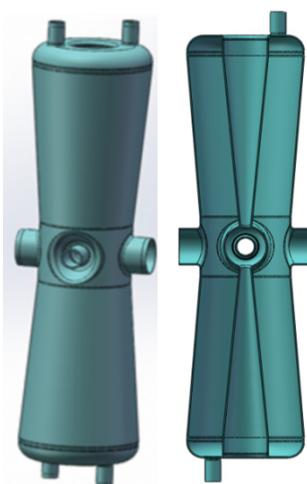


# HWR cavities design parameters

## Properties of HWR cavities

Properties	low-beta	high-beta
Frequency (MHz)	162.5	162.5
$\beta_g$	0.09	0.16
Beam aperture (mm)	40	40
Coupler port diameter (mm)	80	80
$L_{cav} = \beta\lambda$ (mm)	166	295
$E_{pk}/E_{acc}$	5.3	4.7
$B_{pk}/E_{acc}$ (mT/(MV/m))	6.4	6.8
R/Q ( $\Omega$ )	255	264
G ( $\Omega$ )	39	58
Thickness (mm)	3	3
Operating gradient (MV/m)	6	6.5

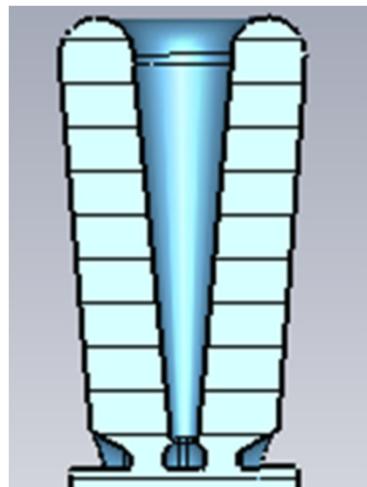
- Large aperture
- Taper type
- Ring-shaped center conductor



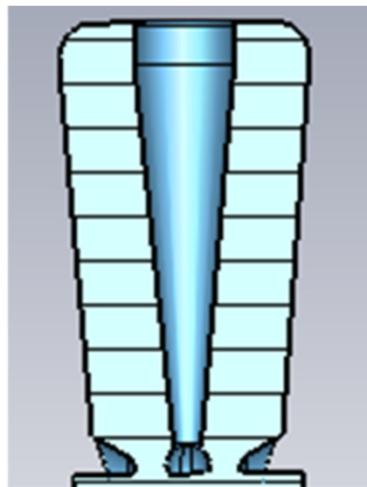
# HWR009 Multipacting simulation

- HWR cavity might have Multipacting at the short plate.
- HWR cavity with flat asymmetric short plates has lower MP intensitiy compared to the HWR cavity with round short p

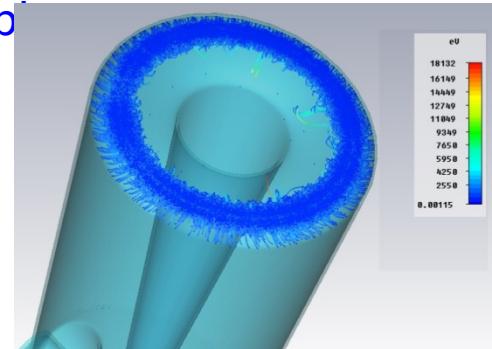
Different shapes of short plates of HWR cavity



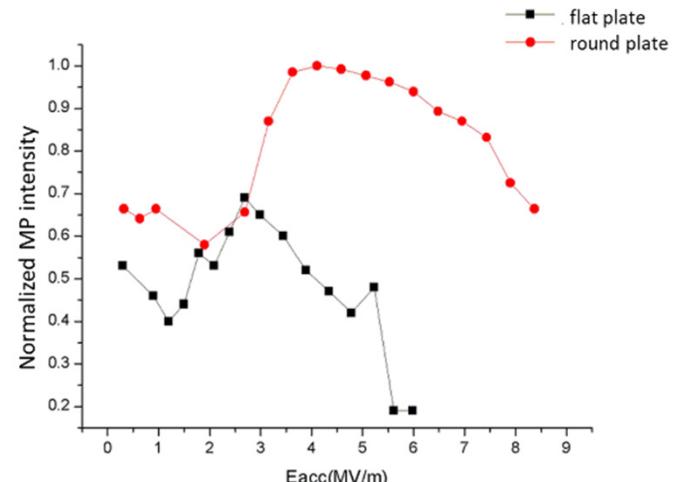
round shape



asymmetric flat shape

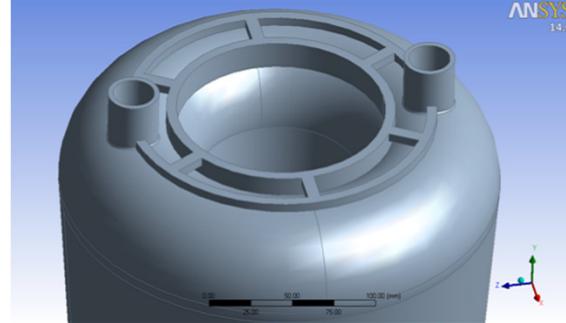


Location of MP electrons near the short plate



MP instensity for two different HWR cavities

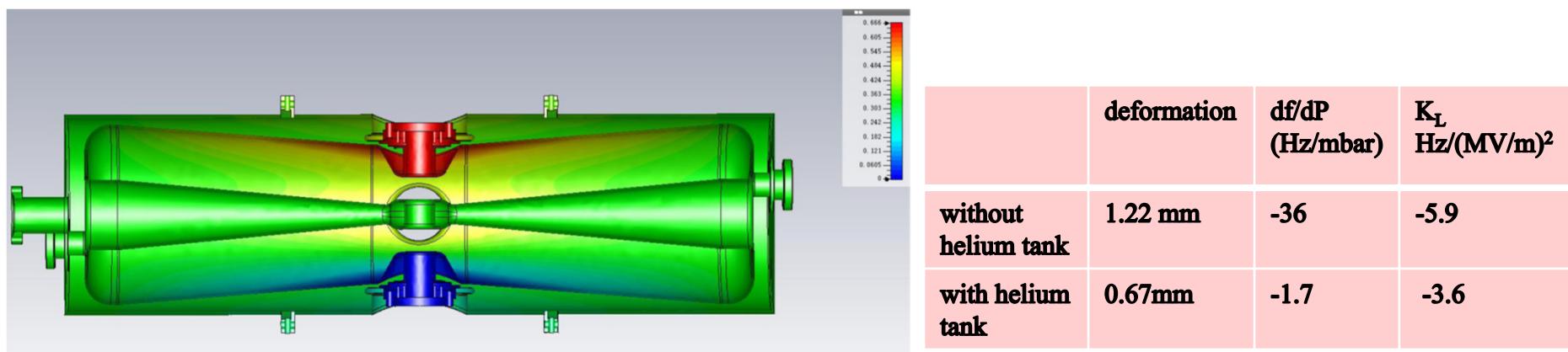
# Mechanical Properties



Stiffening rings at the short plates

- **$df/dP$  caused by the electric filed area deformation is negative,  $df/dP$  caused by the magnetic filed area deformation is posive**
- **By adding stiffening rings at the short plate,  $|df/dP|$  can change to <1 Hz/mbar.**

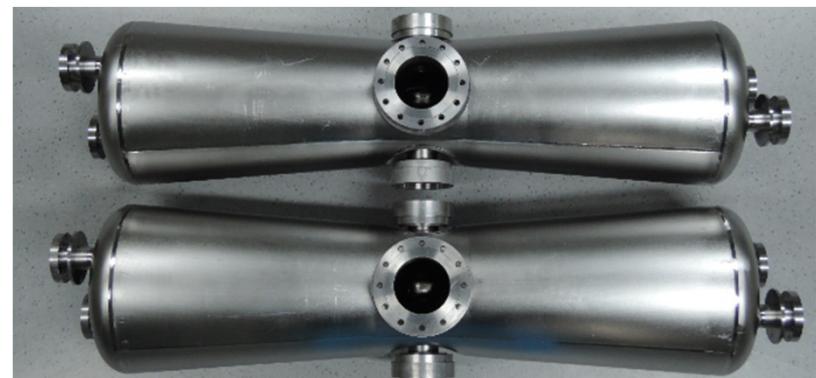
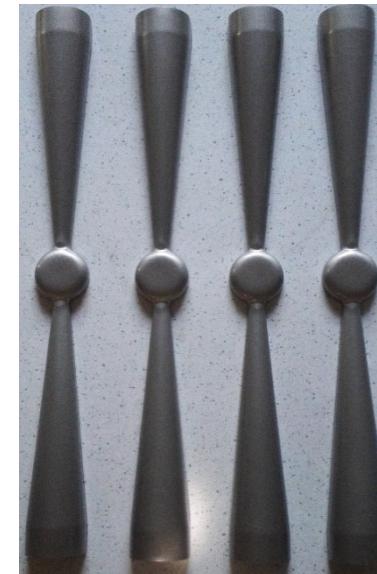
Cavity with different boundary condition	$df/dp(\text{Hz}/\text{mbar})$	$K_L(\text{Hz}/(\text{MV}/\text{m})^2)$
HWR with stiffening rings @ beam ports fixed	-0.1	-0.3
HWR @ beam ports free	-36.0	-5.98
HWR @ beam ports fixed	3.0	-0.41



Cavity deformation when 3000N is applied on one cavity beam pipe flange, while keeping the other flange fixed.



# Cavity fabrication



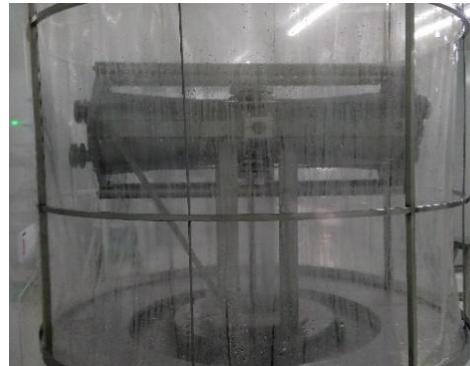


# Cavity treatment and vertical

tecto



HWR high temperature treatment



HWR HPR



HWR BCP treatment

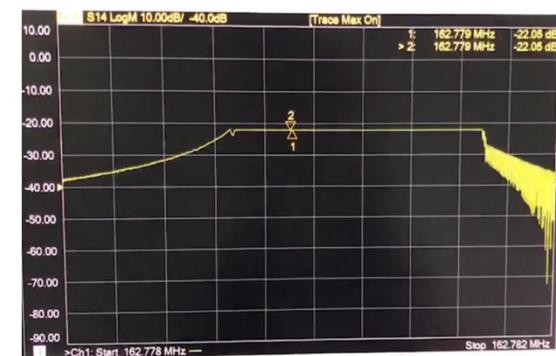
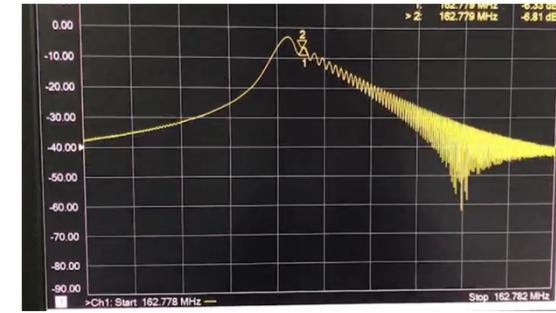
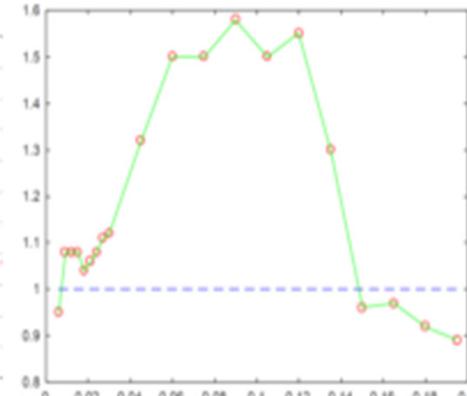
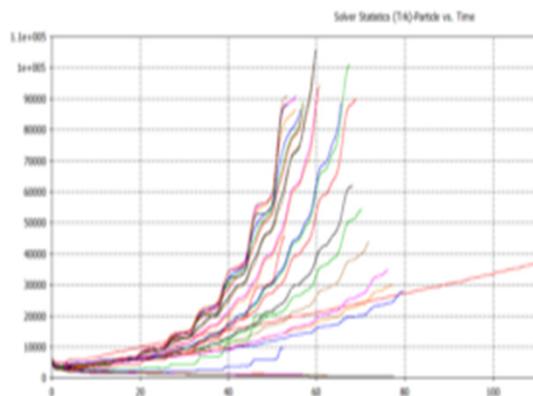
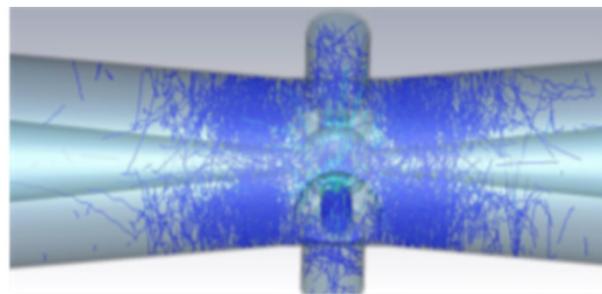
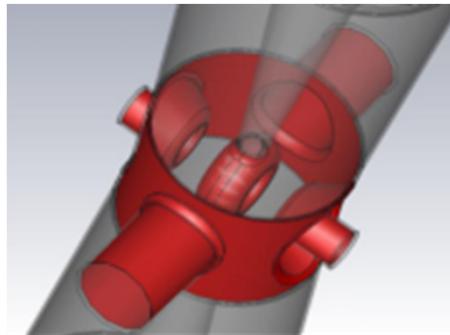


$Q_e$  adjustable, four orders of magnitude. Antenna moving range:  $\pm 20\text{mm}$ . HWR vetical test



# MP during cavity vertical test

## HWR009 MP simulation



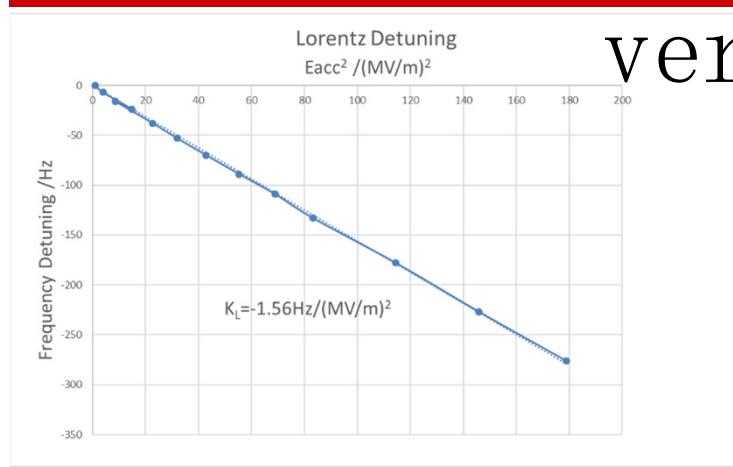
MP conditioning at frequency sweeping modes at 4.2K

MP was found when the field is quite low (lower than  $1\text{MV/m}$ ). CST MP simulation gives that MP might happen at the eletric field areas when the gradient is  $0.02\text{--}0.15\text{ MV/m}$ , which is coincident with the simulation result.

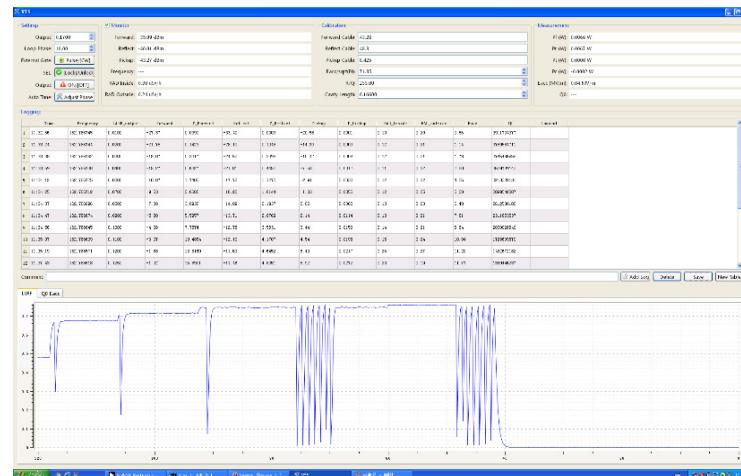
After one day's conditioning, MP disappeared.



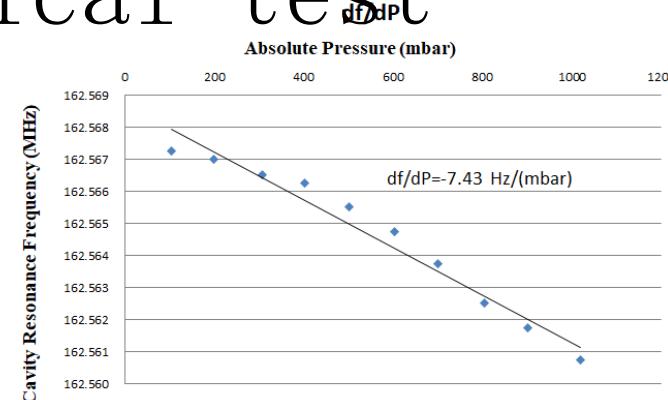
# Cavity properties during cavity vertical test



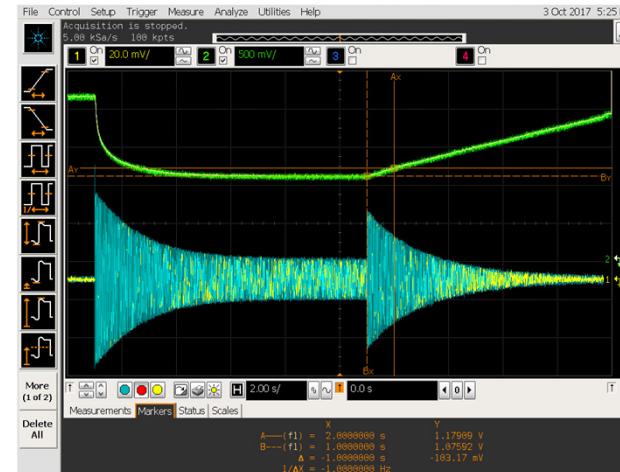
Vertical test, HWR009 Lorentz detuning,  
 $K_L = -1.56 \text{ Hz}/(\text{MV/m})^2$



Cavity processing as power increased



Vertical test, HWR009  
 $df/dP = -7.43 \text{ Hz}/(\text{mbar})$



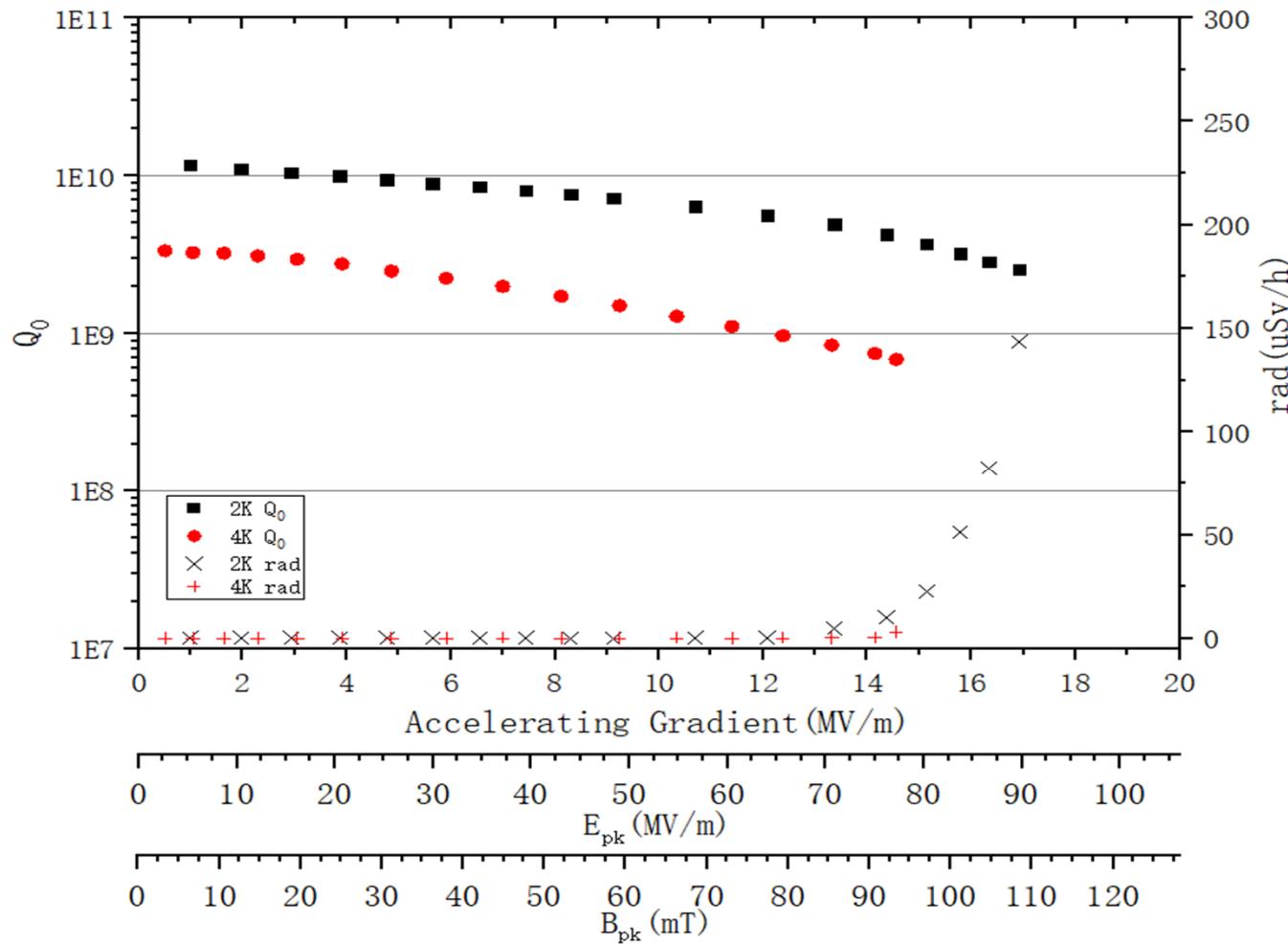
RF signals



# Taper type HWR009 vertical test

BCP  
HPR  
800°C

re



**Vertical test result of  $\beta_g=0.09$  162.5MHz HWR cavity**  
**The gradient reached 17MV/m, and  $E_p$  was about 90MV/m at 2K.**



# Summary

- Primary beam dynamic simulation of BISOL high current deuteron accelerator has been carried out. The simulation results predict that the proposed design can accelerate safely a 10 mA deuteron CW beam to 40 MeV. And the emittance growth and halo formation are under control.
- A  $\beta_g=0.09$  162.5MHz taper type HWR cavity was designed to accelerate deuteron beams with CW current of 50 mA. The vertical test showed it had high gradient and good mechanical properties. The maximum gradient reached 17 MV/m.
- Studies on front-end of BISOL deuteron accelerator has also been carried out. PKU ECR ion sources can produce 120 mA  $H^+$  and 83 mA  $D^+$  beams. A 50mA  $D^+$  RFQ has been designed and fabricated and under beam loading test.



# Acknowledgement

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To members of the PKU BISOL collaboration who have contributed to the study of BISOL deuteron accelerator.



*Thank you!*