High availability oriented physics design for CiADS proton linac

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Outline

- Brief introduction of CiADS project
- Beam dynamics design facing beam loss control
- Beam recovery for high availability
- Summary

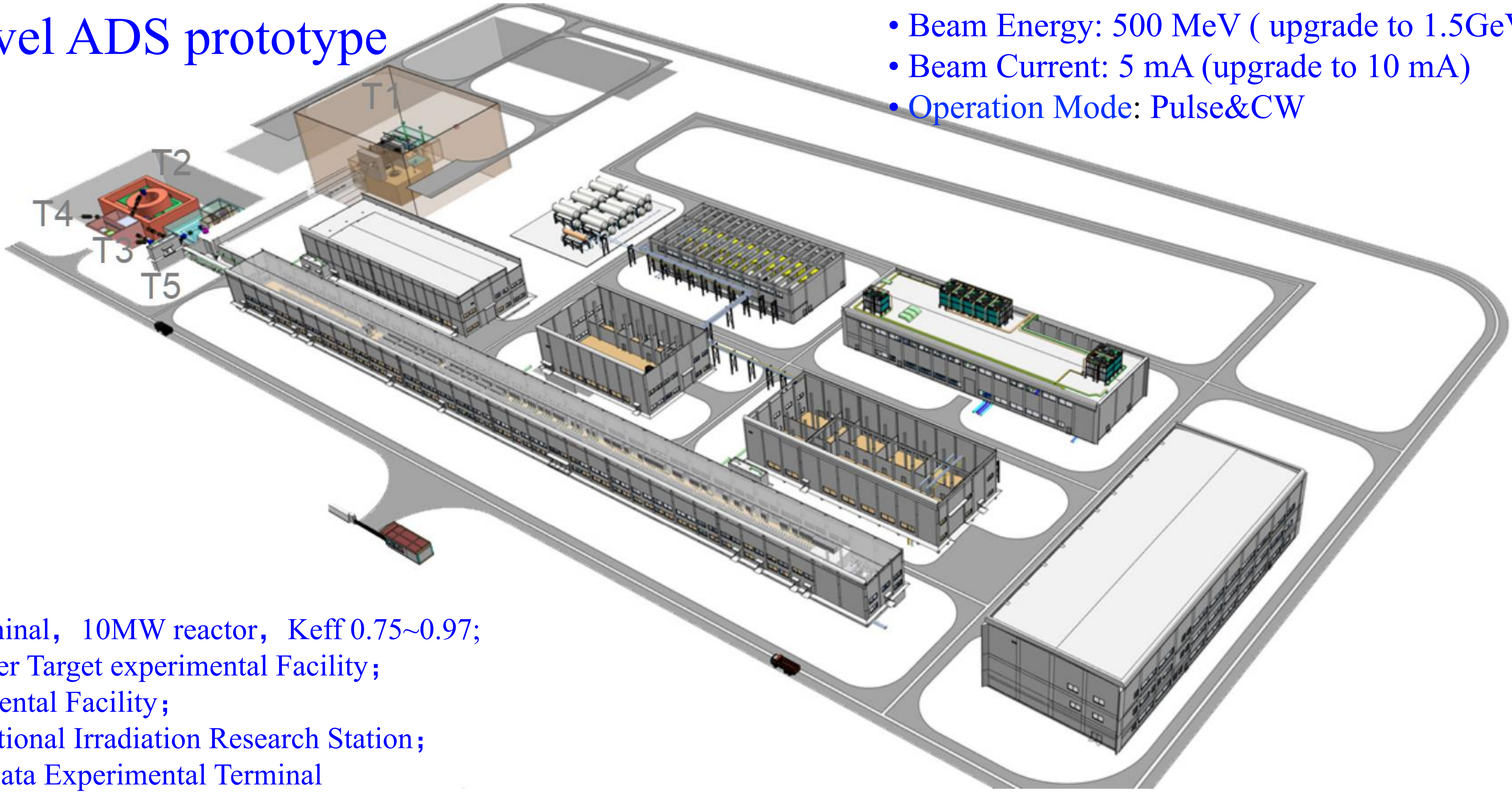
Brief introduction of CiADS project

- **Approved in Dec. 2015, Ground broke in August 2018, Officially started in July 2021**
- **Leading institute: IMP**
- **Budget: ~4 B CNY (Gov. 1.8B + CNNC 1.0 B + Local Gov. 1.2 B)**
- **Location: Huizhou, Guangdong Prov.**
- **Partners: CIAE, CGN, IHEP, etc.**

Brief introduction of CiADS project

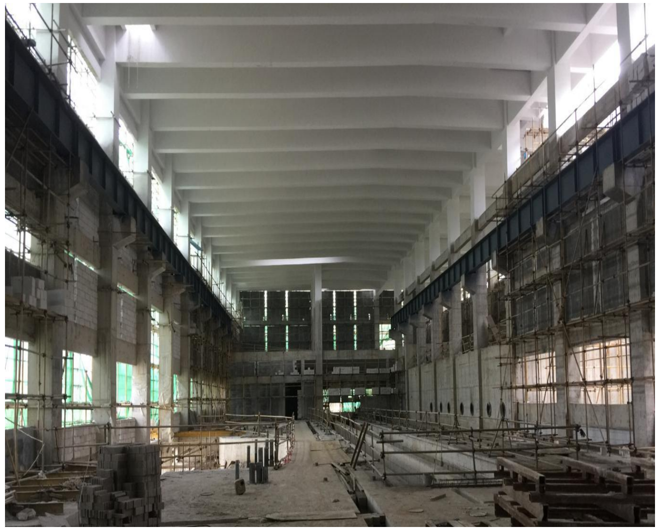
MW-level ADS prototype

- Beam Energy: 500 MeV (upgrade to 1.5GeV)
- Beam Current: 5 mA (upgrade to 10 mA)
- Operation Mode: Pulse&CW

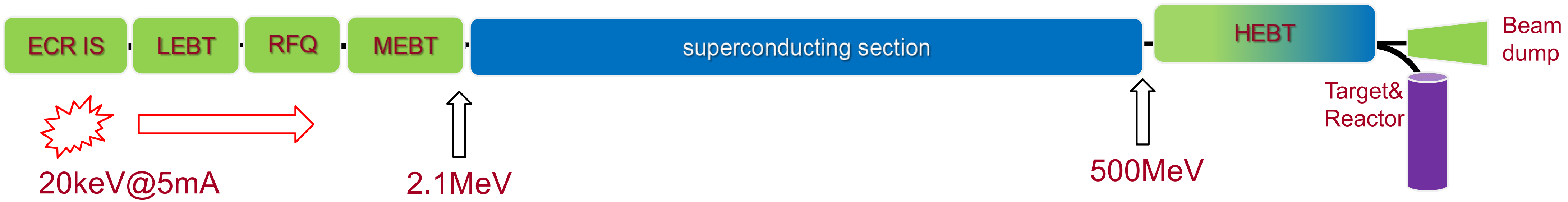


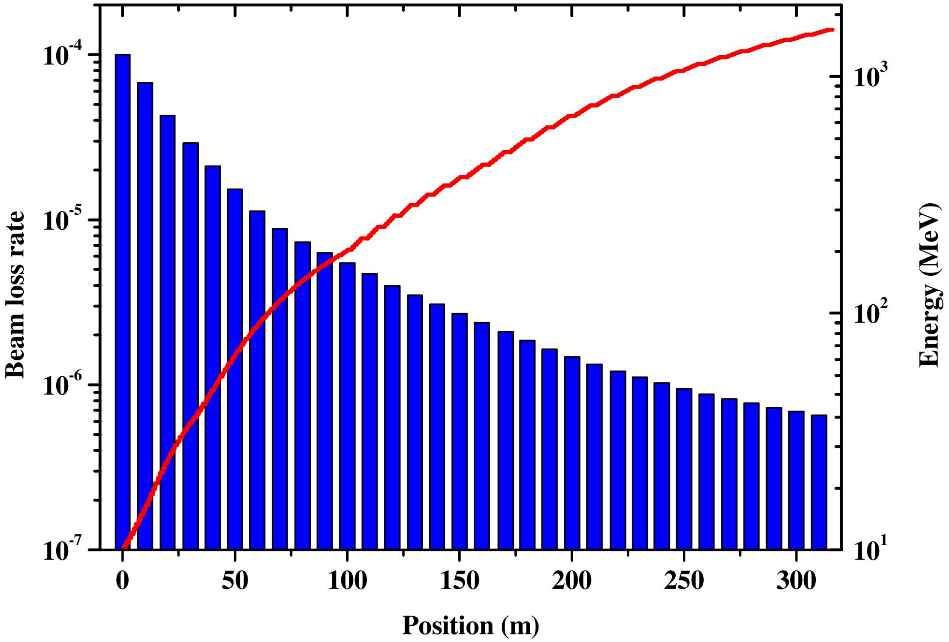
- T1: ADS Terminal，10MW reactor，Keff 0.75~0.97;
- T2: High power Target experimental Facility；
- T3: μ experimental Facility；
- T4: Multifunctional Irradiation Research Station；
- T5: Nuclear Data Experimental Terminal
- T6: ISOL for upgrade

Brief introduction of CiADS project



Challenge of sc-Linac for CiADS





Beam Trip Duration	Industrial Scale Transmutation	Remarks
T<1sec	<25000	Target window lifetime
1sec<T<10sec	<2500	Fatigue failure of fuel cladding
10sec<T<5min	<2500	Fatigue failure of inner barrel and reactor vessel
T>5min	<50	System Availability

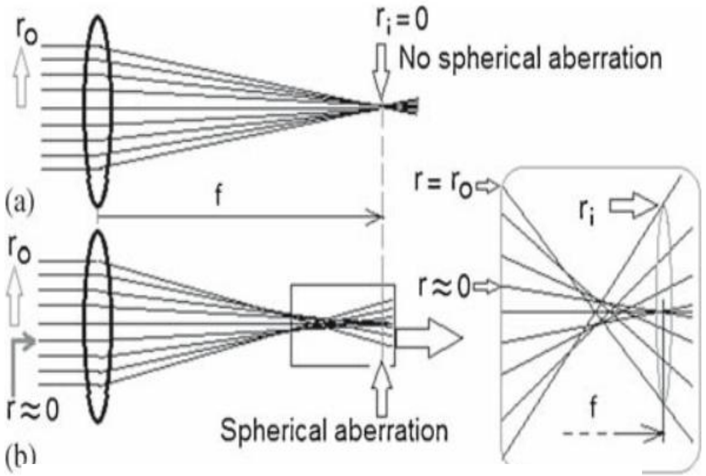
H. Aït Abderrahim et al, Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production. 2010. https://doi.org/10.2172/1847382

Beam loss control + Beam recovery → CiADS Physics

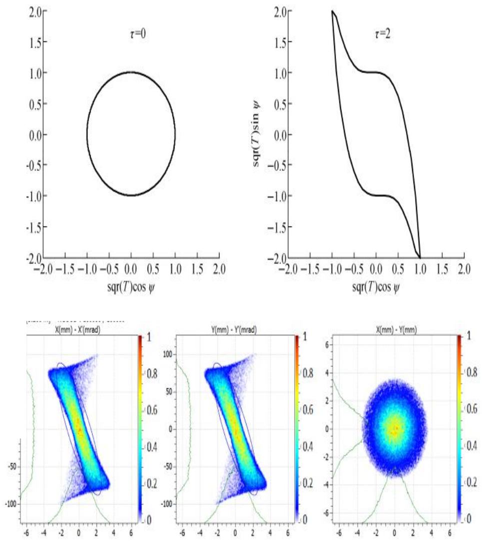
Beam loss control: issue @LEBT

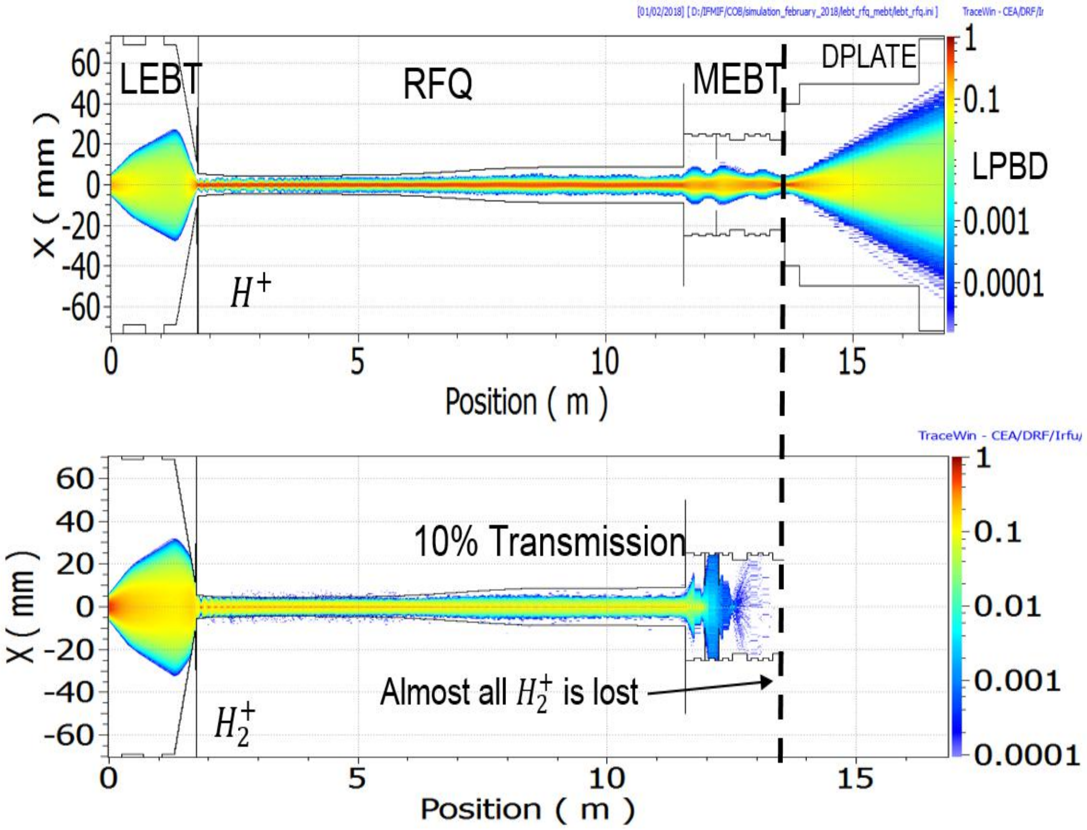
Ref: F. Grespan, Experience from the IFMIF RFQ Commissioning

$$B_z(r,z) = B(z) - \frac{r^2}{2}B''(z) + \frac{r^4}{64}\frac{d^4B(z)}{dz} - \ldots \quad \Delta r' = -\frac{r}{f_0}[1 + C_1 r^2 + C_2 r^4]$$



$$\Delta\epsilon_{x,y} = \frac{R^4}{2\sqrt{6}f_0}\sqrt{\frac{C_1^2}{12} + \frac{C_1C_2}{5}R^2 + \frac{C_2^2}{8}R^4}$$



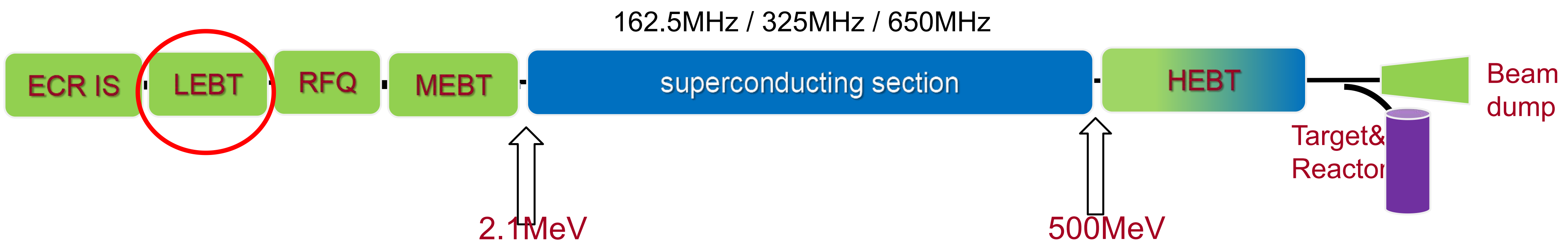


Aberration effect on beam phase space

The main acceleration ion and impurity ion simulation analysis of IFMIF

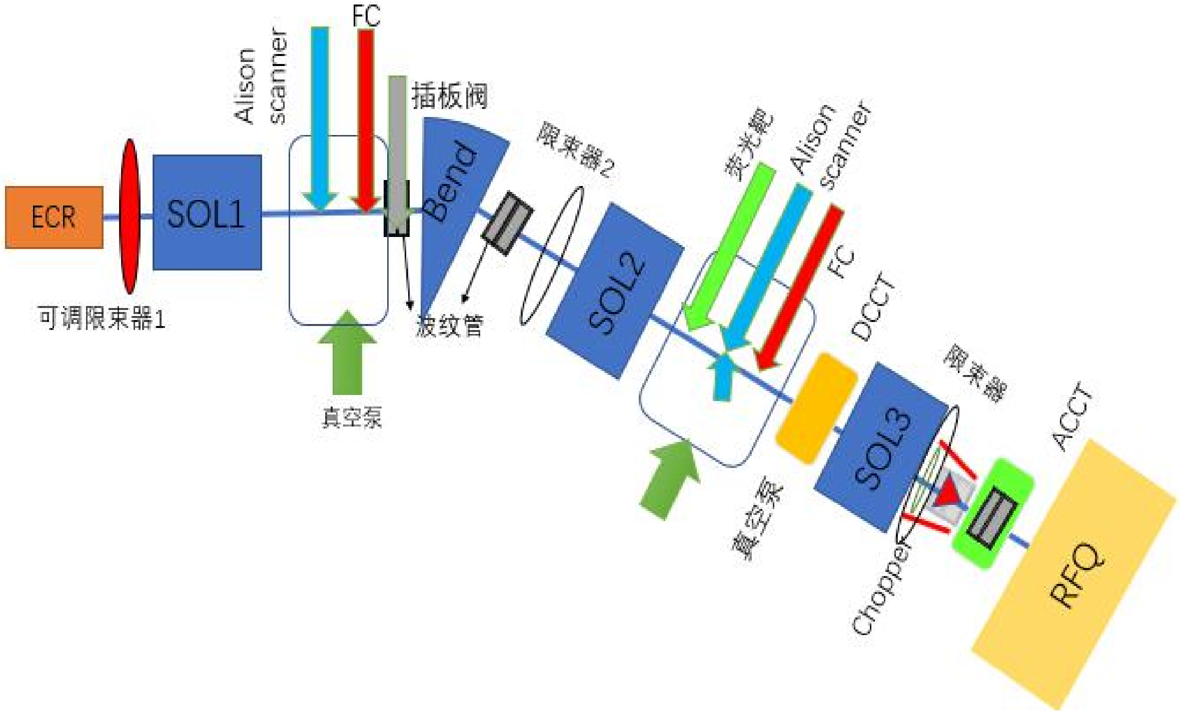
Phase space distortion and Impurity ions is the main reason causing beam loss

Beam loss control: LEBT design

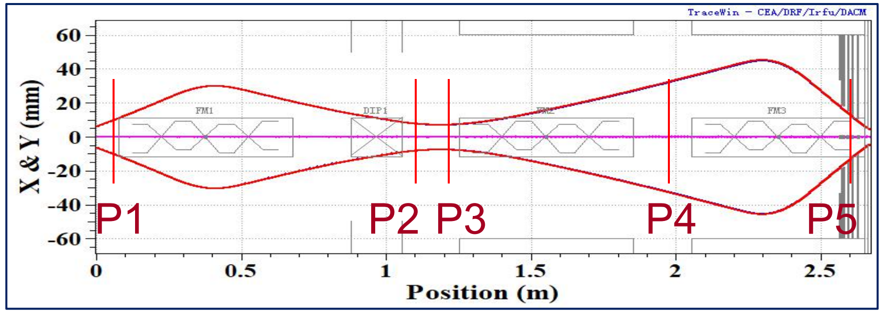


Function of LEBT：

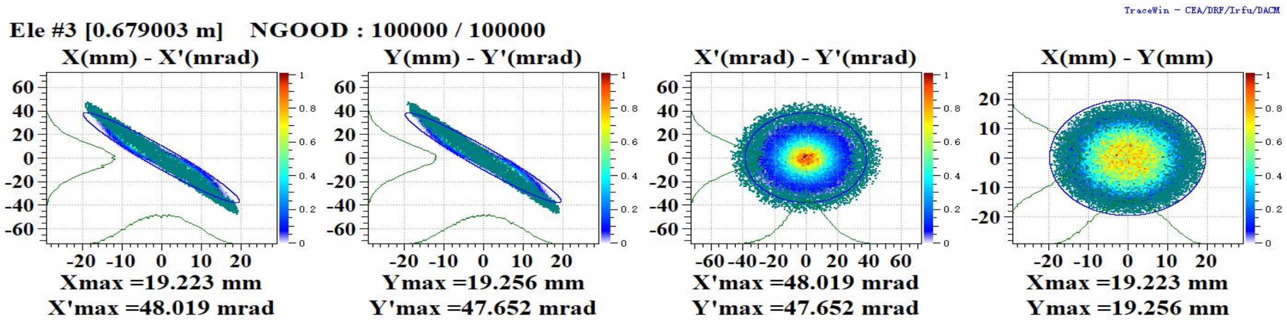
- Beam parameters measurement
- Matching between ECRIS and RFQ
- Transverse beam quality optimization
- Purifying H^+ beam



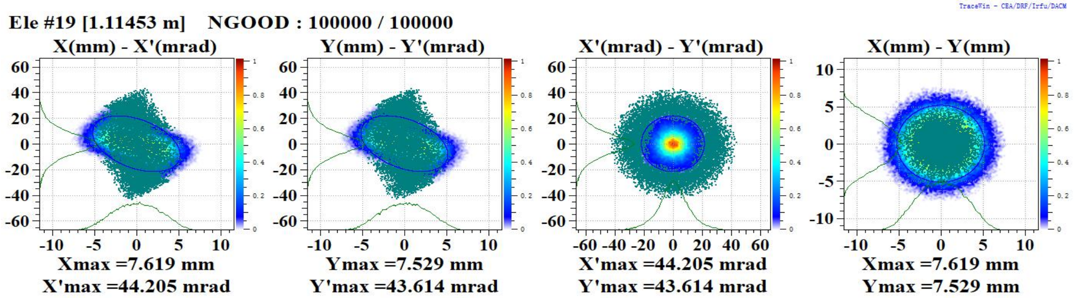
Beam loss control: LEBT design



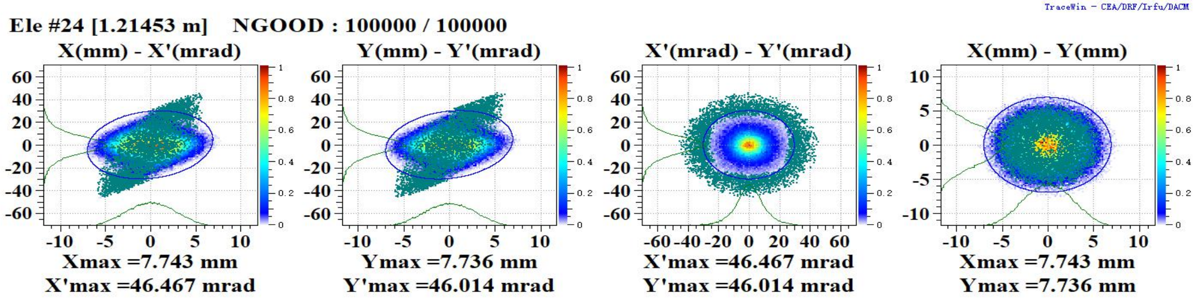
P1 -input of LEBT



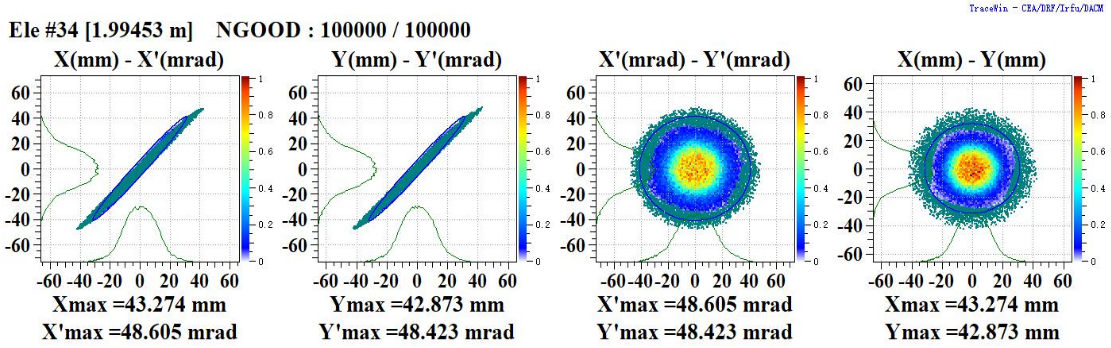
P2 -after the bend



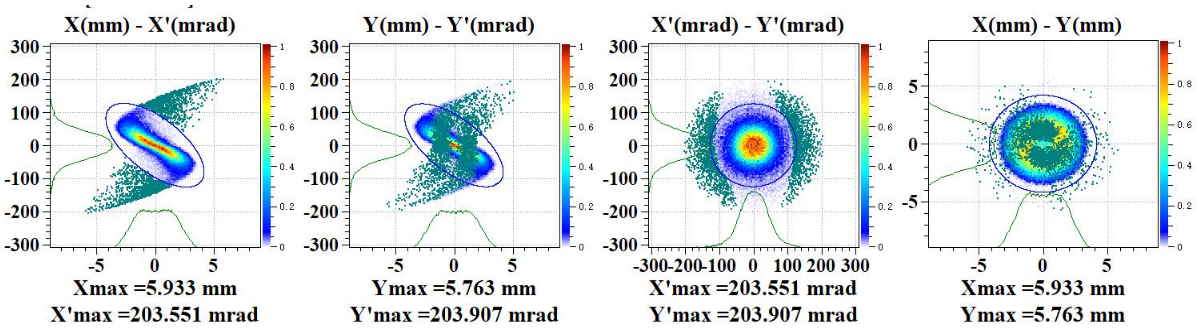
P3 -before solenoid 2



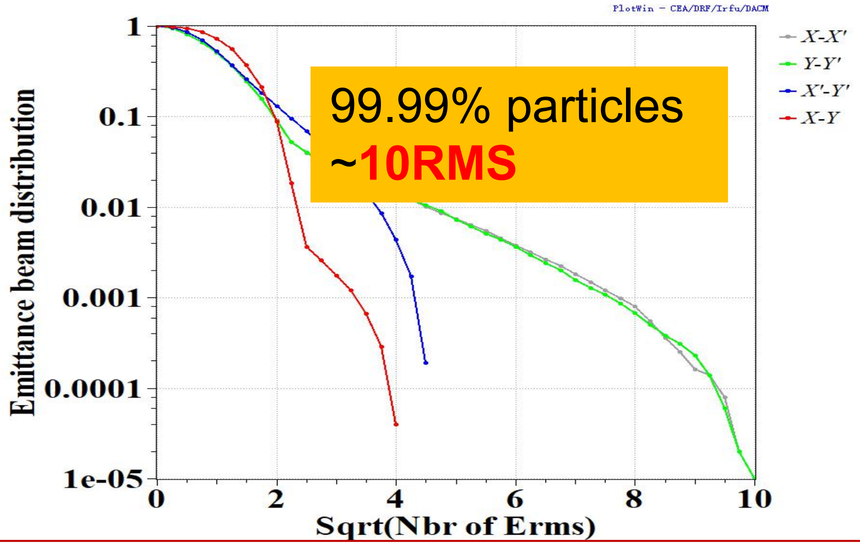
P4 -before solenoid 3



P5 -out of LEBT

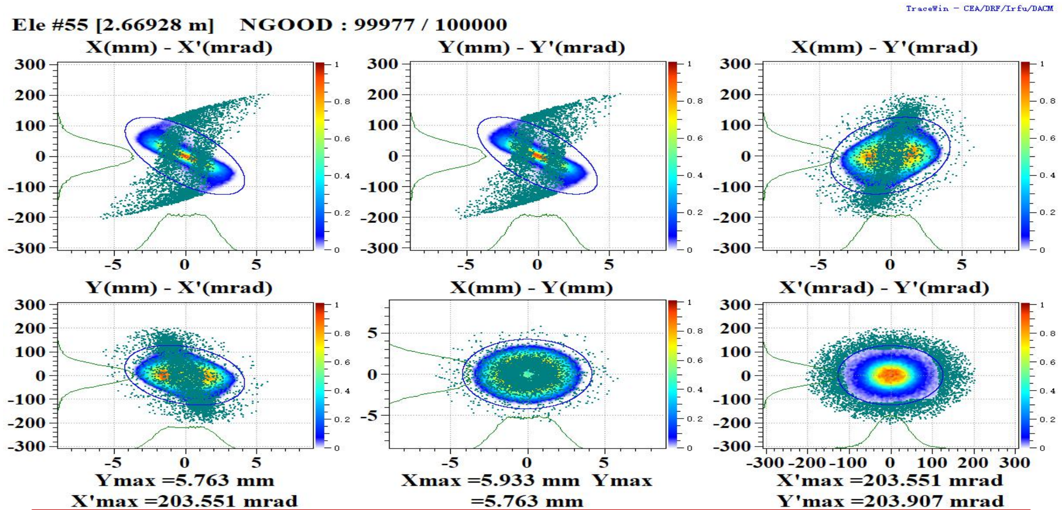


Beam loss control: LEBT design

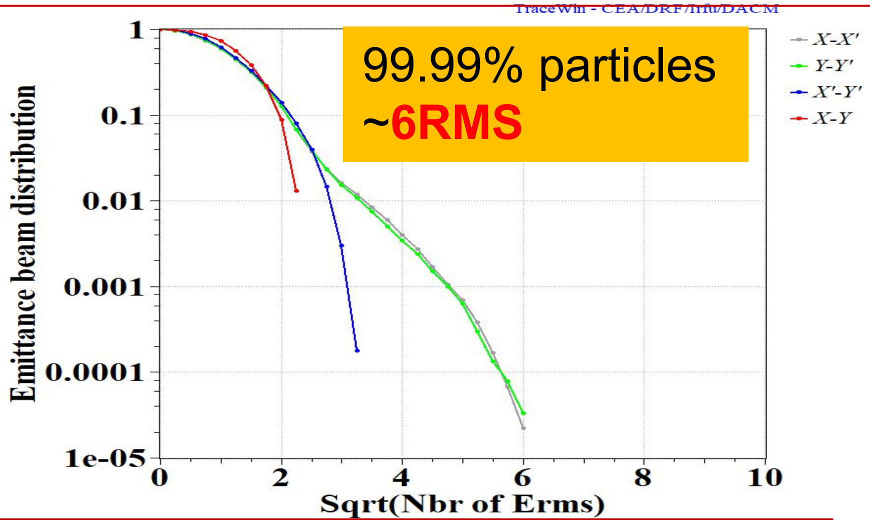


99.99% particles
~**10RMS**

Phase space at the exit of LEBT without scraping

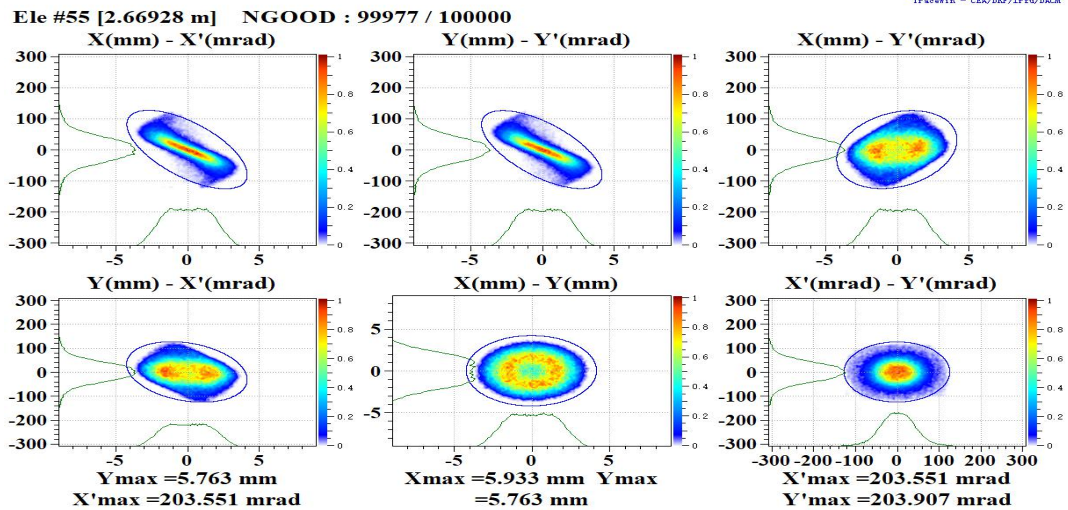


Phase space at the exit of LEBT without scraping



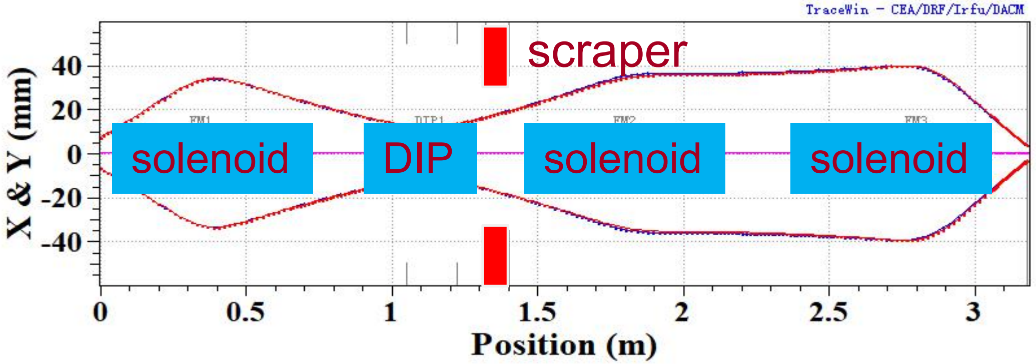
99.99% particles
~**6RMS**

Phase space at the exit of LEBT with scraping

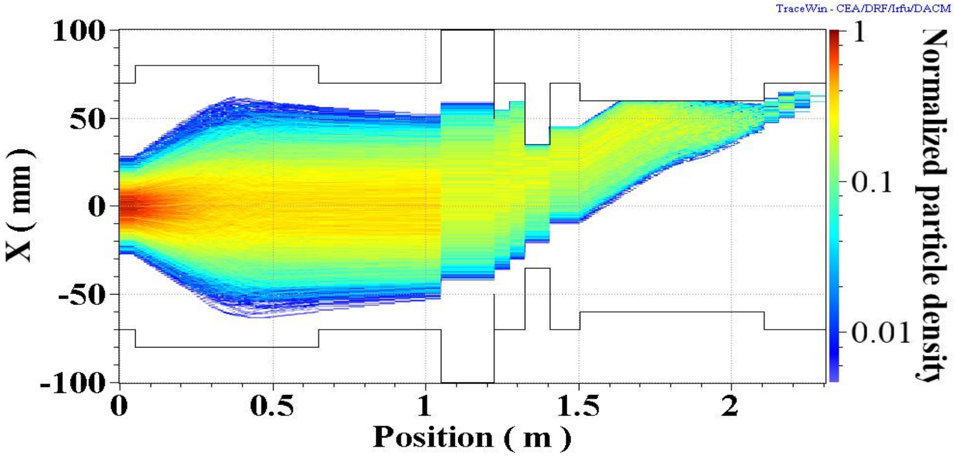


Phase space at the exit of LEBT with scraping

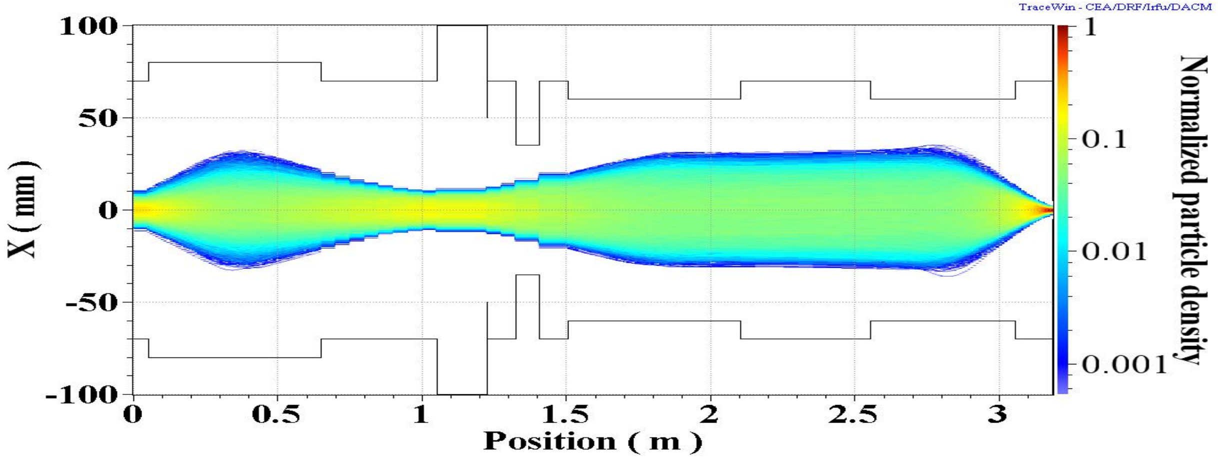
Beam loss control: LEBT design



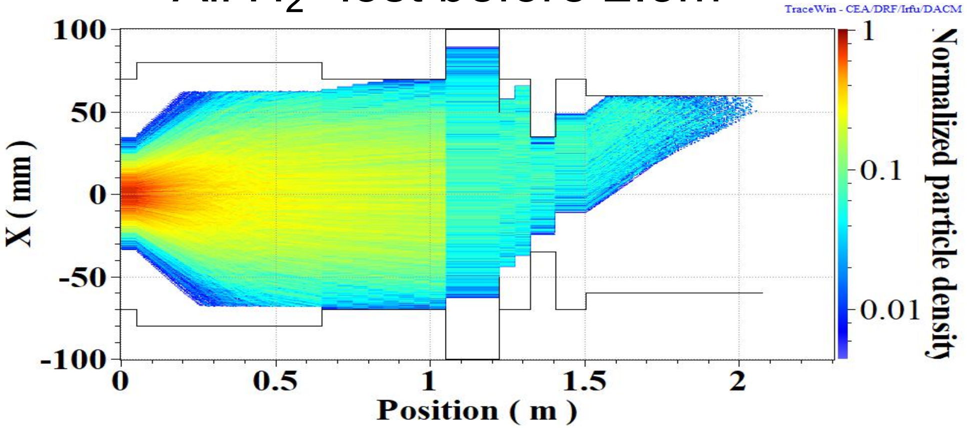
Envelope of H+



All H_2^+ lost before 2.3m



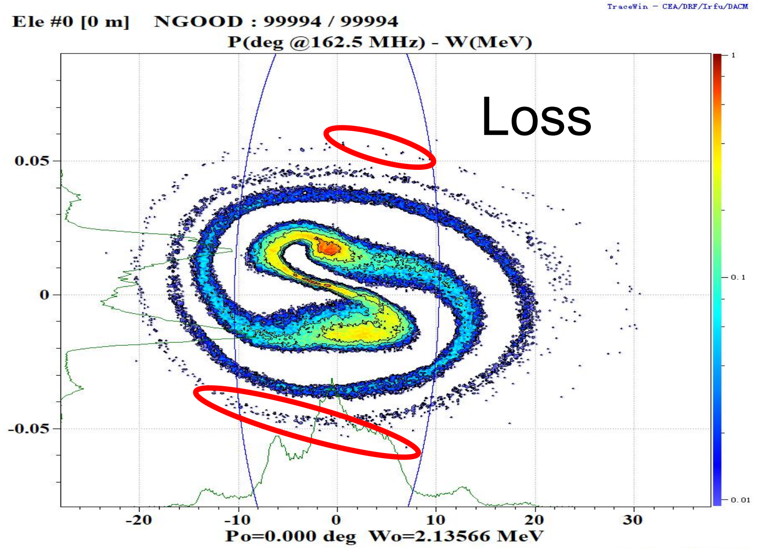
Beam density of H+

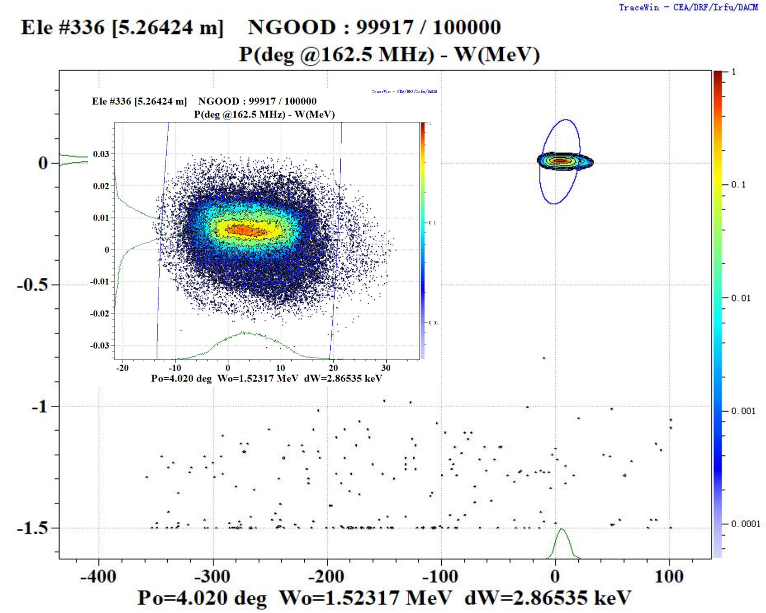


All H_3^+ lost before 2.1m

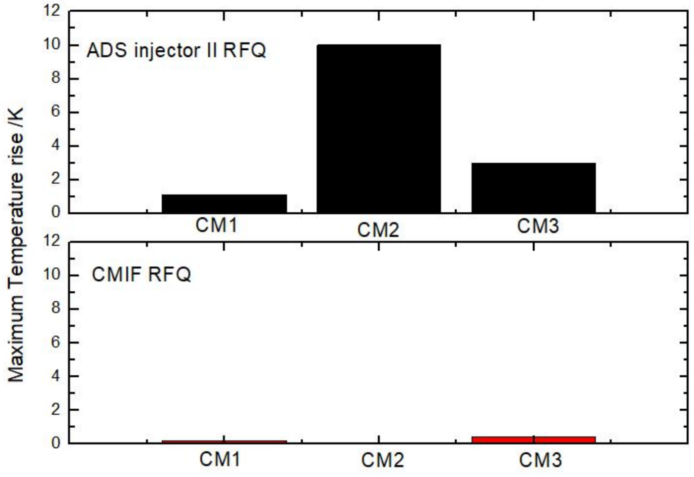
All H_2^+ & H_3^+ are scraped before RFQ

Beam loss control: issue @RFQ

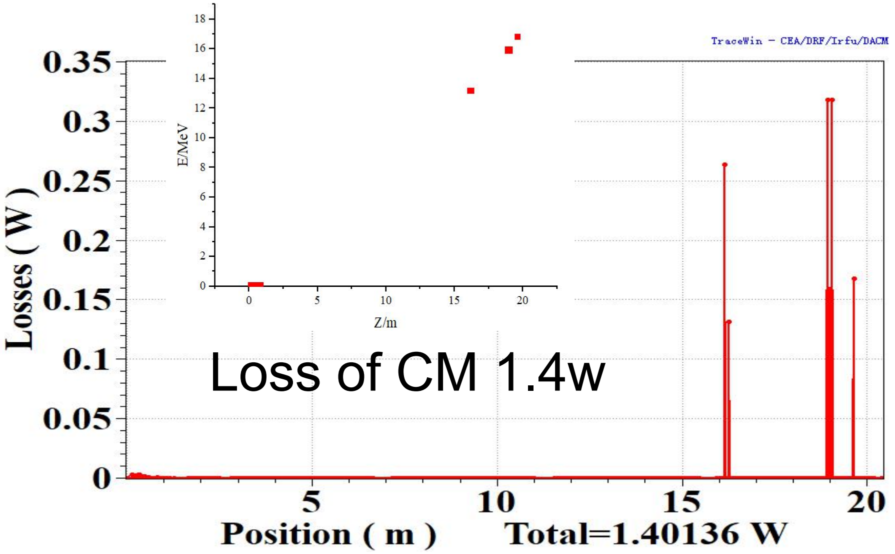


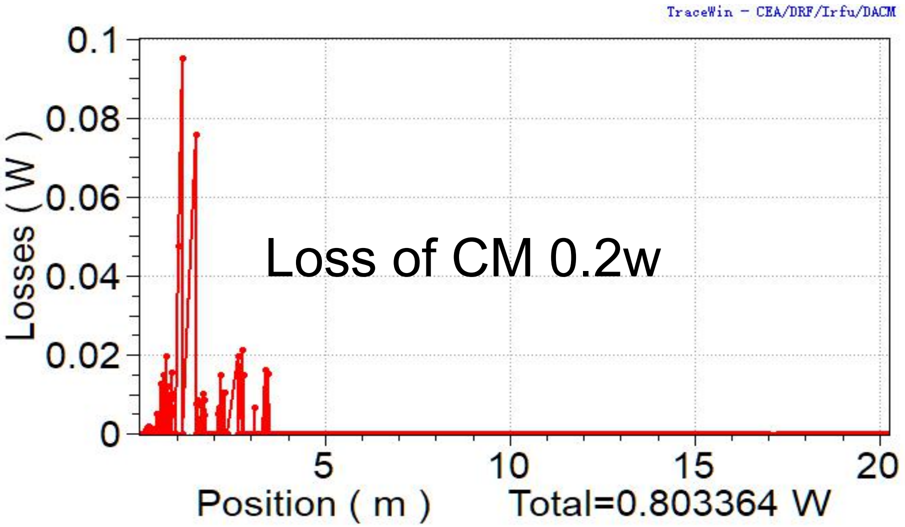


ADS Inj. II RFQ@ 1 mA
Design current 15mA
CMIF RFQ@ 2 mA
Design current 5mA

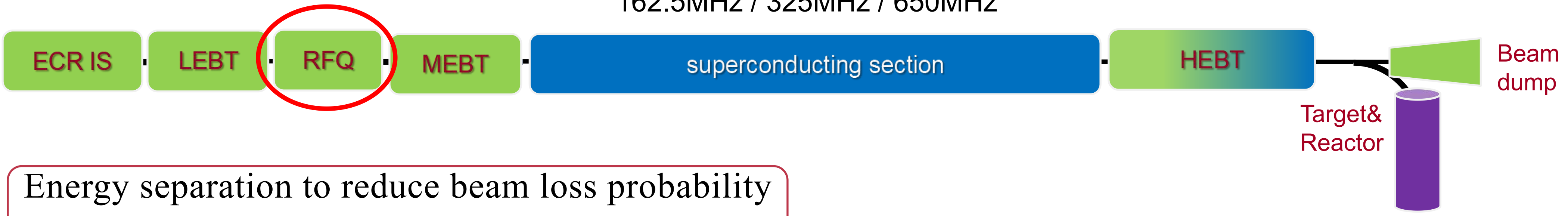


The maxinum temperature rise of CM with ADS injectorII RFQ is 25 times than one with CMIF RFQ



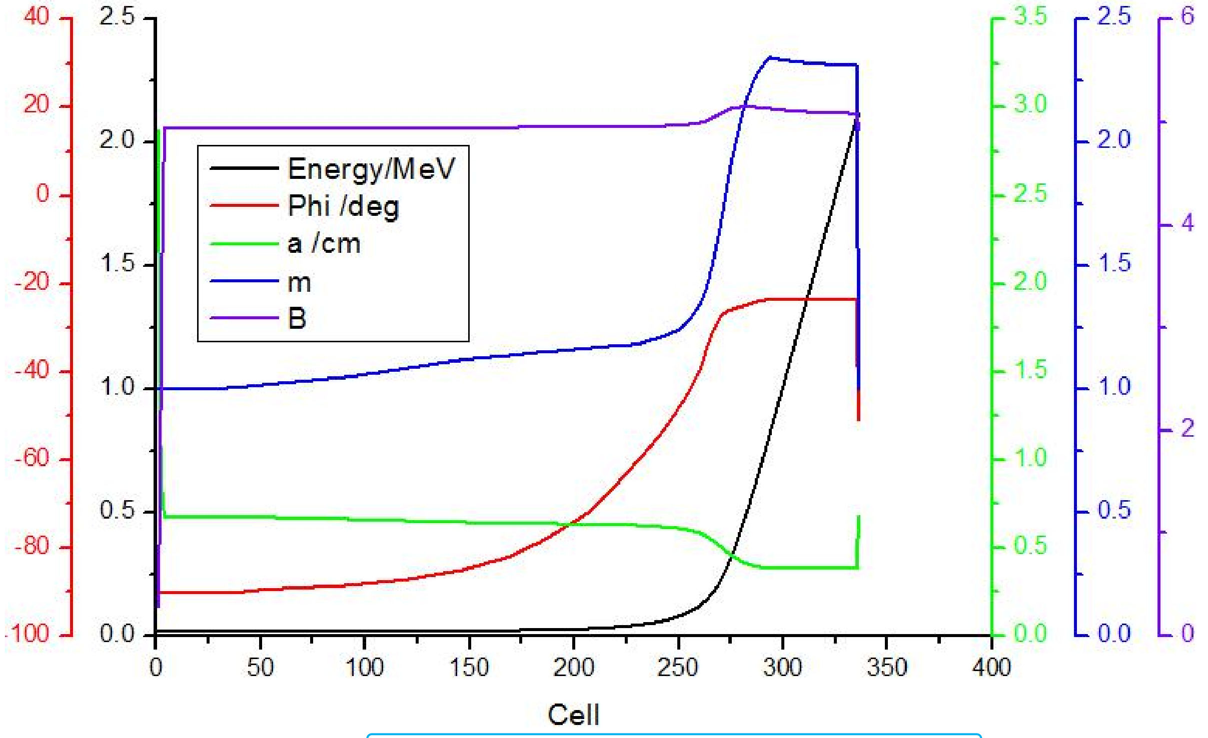


Beam loss control: RFQ design



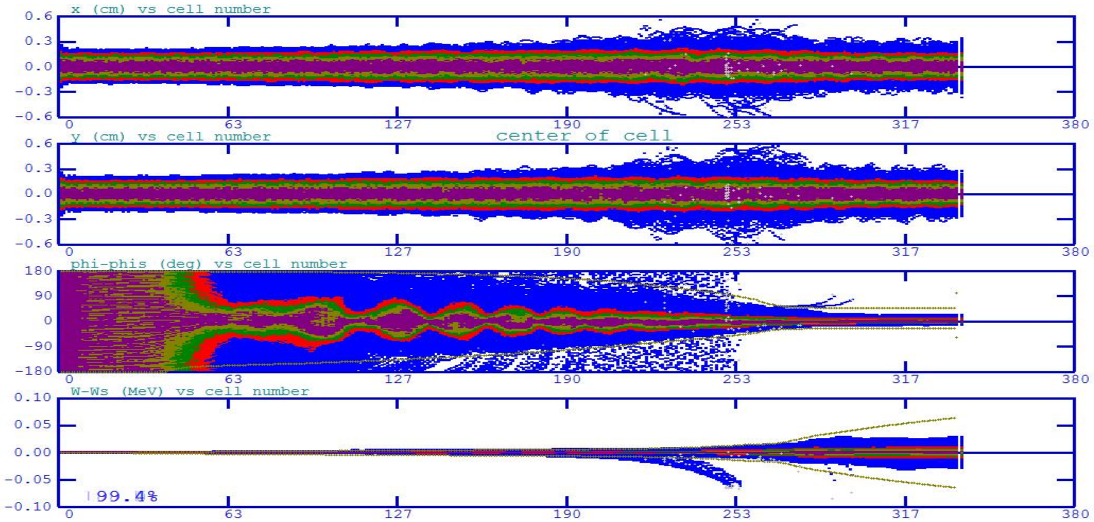
- Energy separation to reduce beam loss probability in the downstream linac
- Full particle optimization aimed at 99.99% longitudinal emittance at bunching segment
- Smooth transition to prevent emittance increase caused by parameter mutation at transition segment

Parameters	value
Vane voltage （kV）	65
Max surface electric field（MV/m）	13.59@kp=1
Average aperture(mm)	6.79
Length (m)	4.90
transport effeciency/acceleration efficency	99.6/99.4
Long.rms emit(mm.mrad)	0.209
Long.99.99% emit(mm.mrad)	3.53

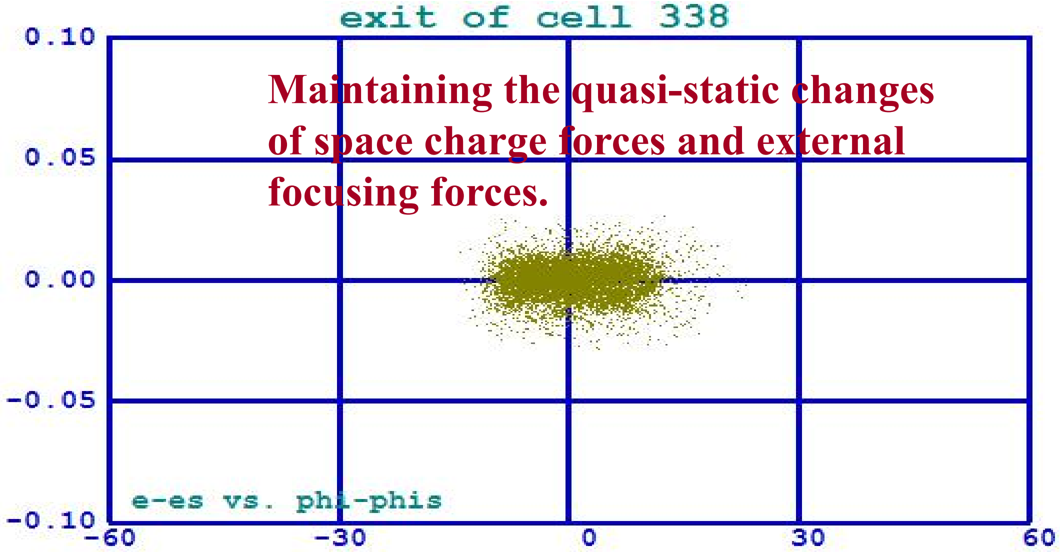


The main parameters of RFQ vs cell

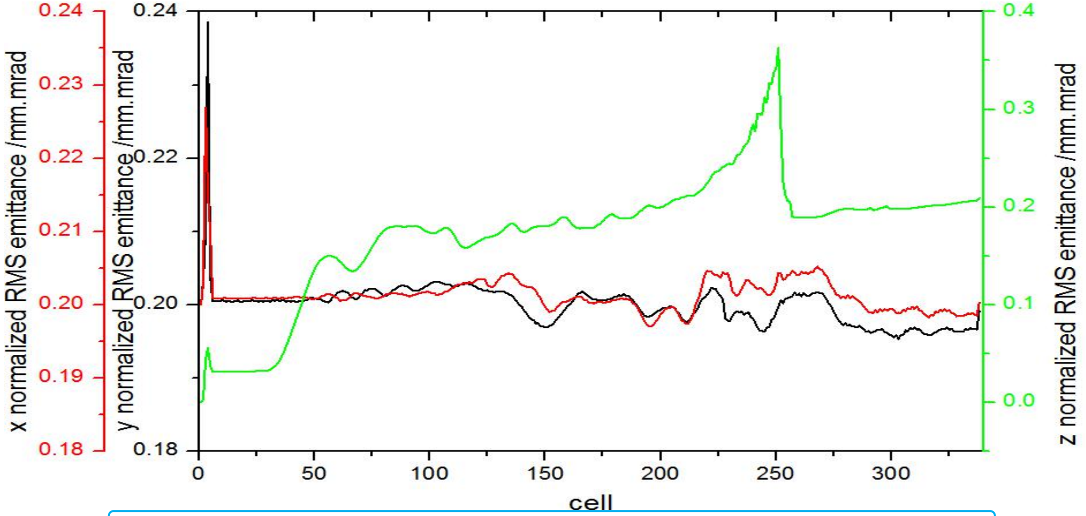
Beam loss control: RFQ design



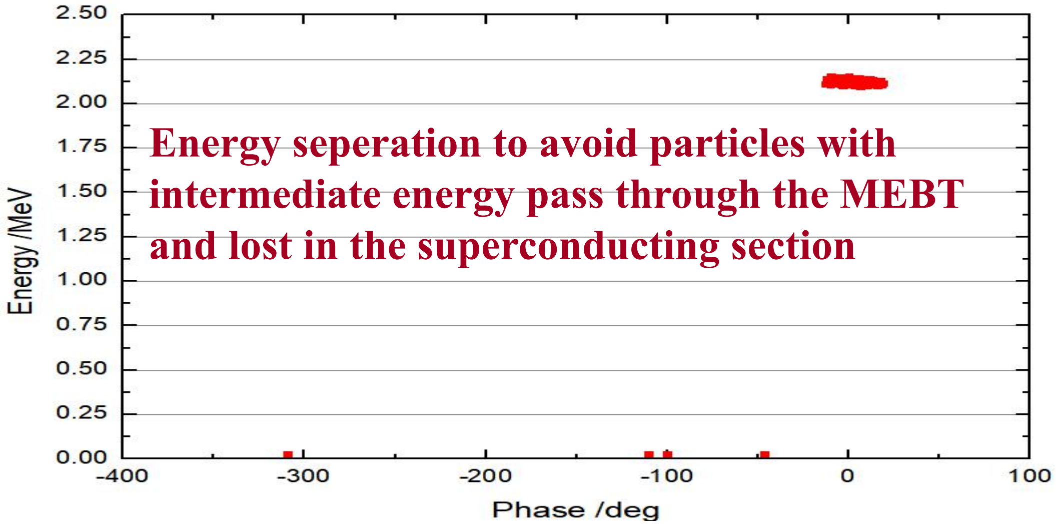
The evolution of transverse and longitudinal envelope



The longitudinal phase space



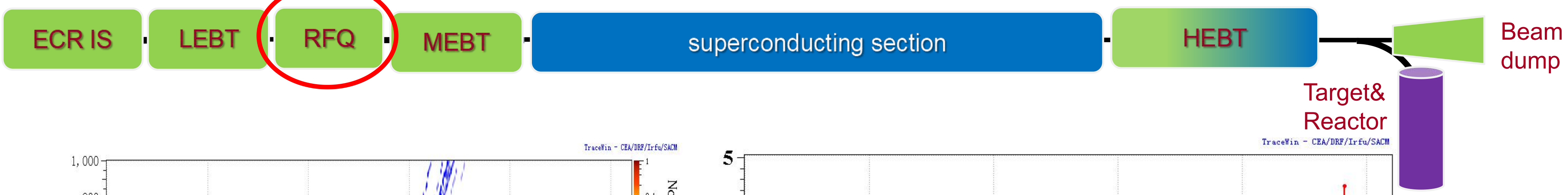
The evolution of transverse and longitudinal emittance



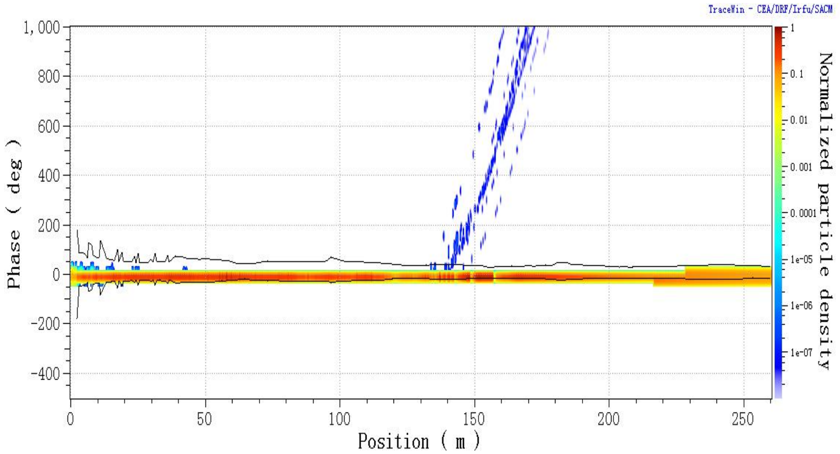
Main bunch and particles with lower energy at RFQ output

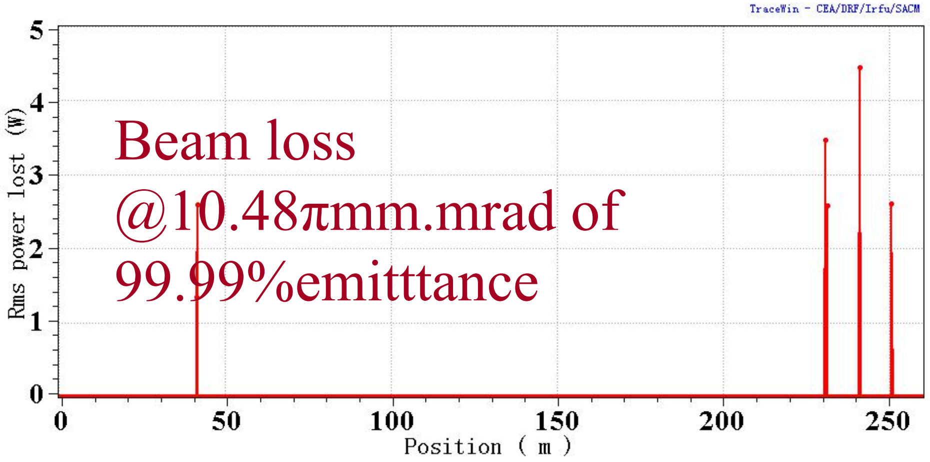
Beam loss control: RFQ design

162.5MHz / 325MHz / 650MHz

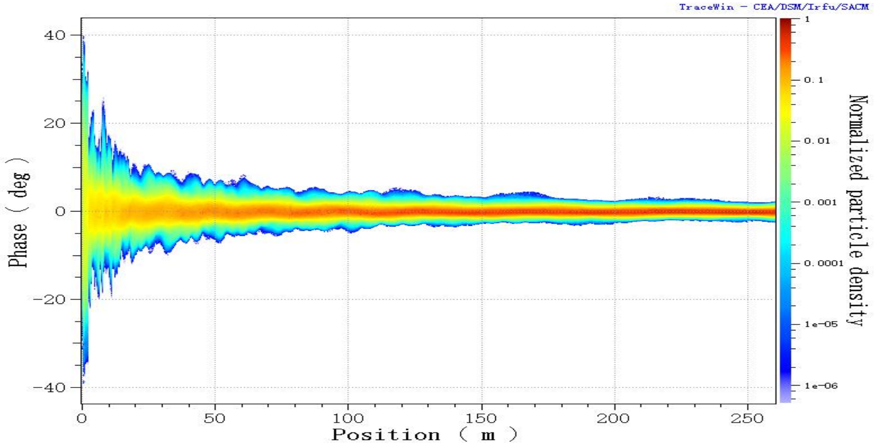


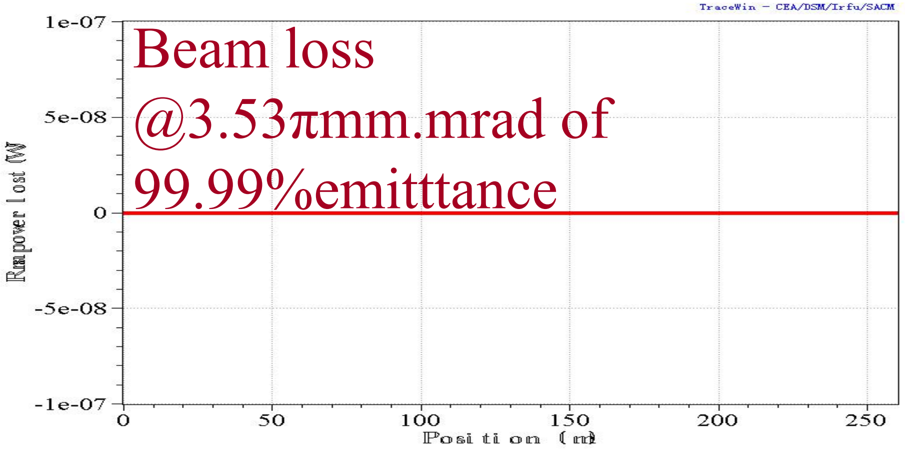
RFQ for injectorII



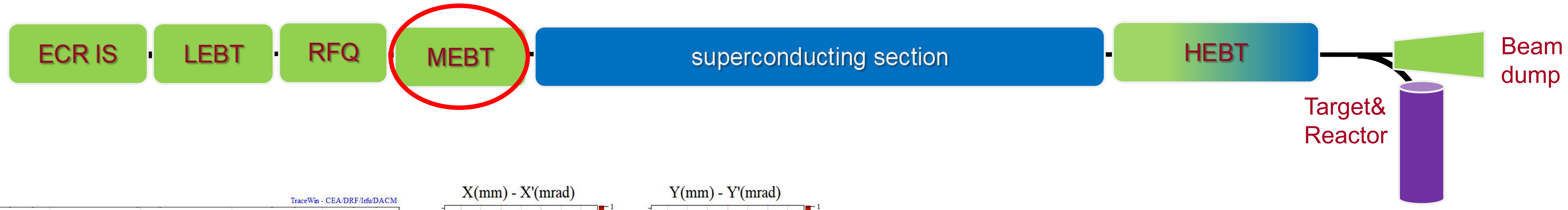


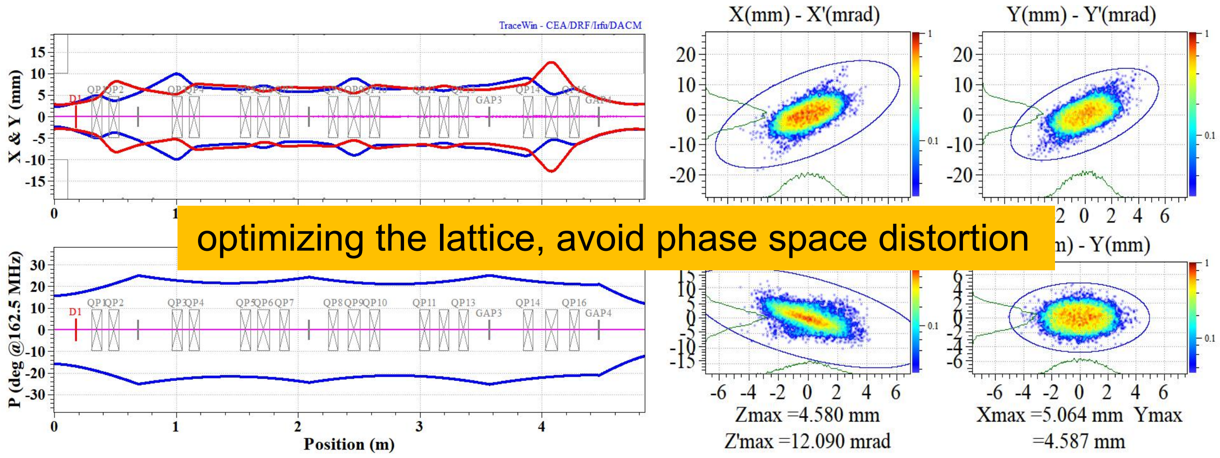
RFQ for CIADS





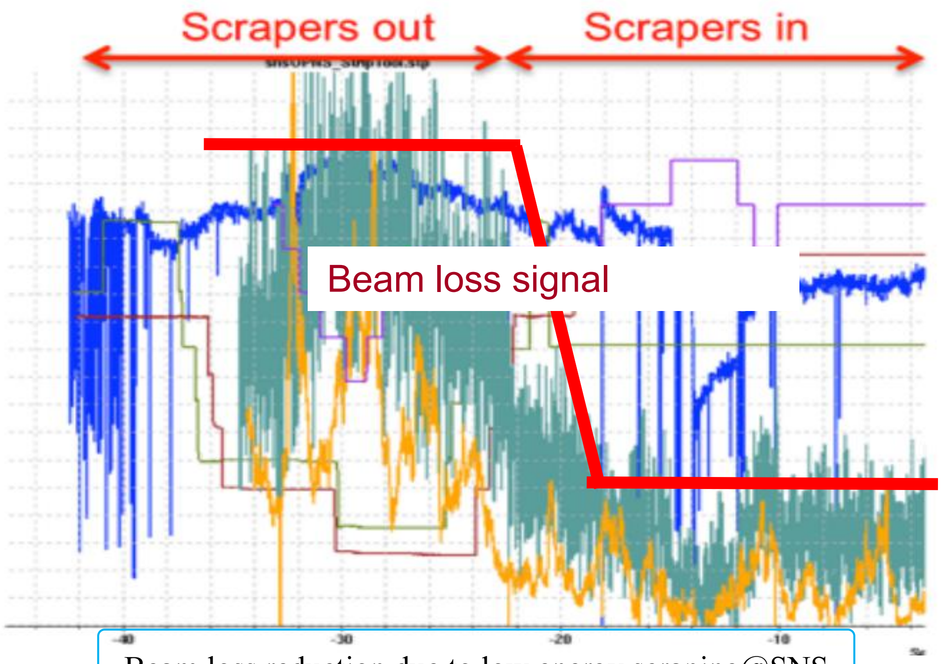
Beam loss control: MEBT design





- Matching between RFQ and superconducting section
- Beam parameters measurement
- Beam quality optimization:full space scraping method to reduce halo particle loss in the downstream linac

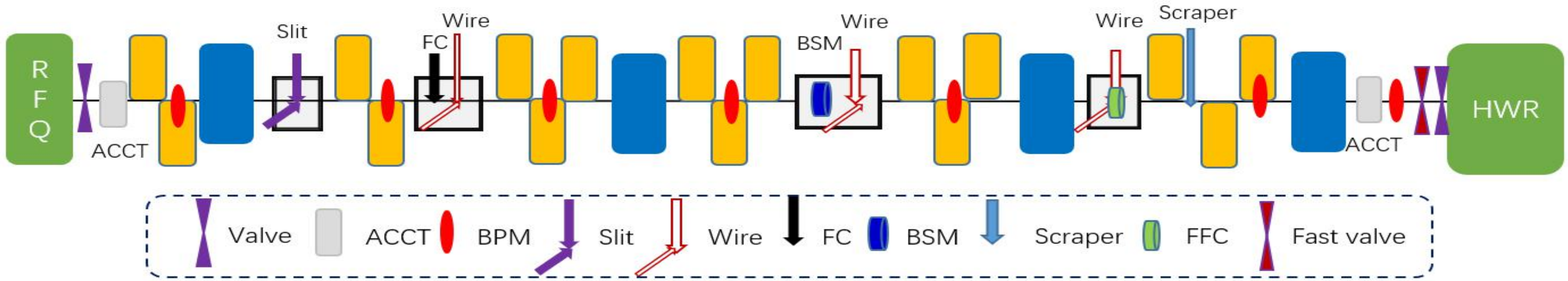
Scraping at low beam energy in the MEBT has proven to be very effective for SNS.



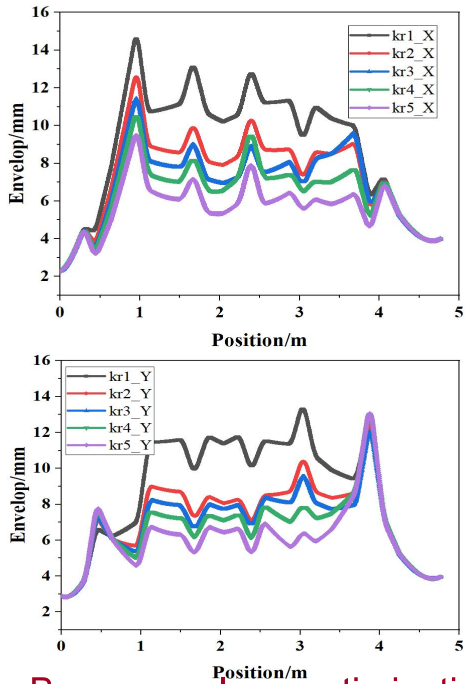
Beam loss reduction due to low energy scraping@SNS

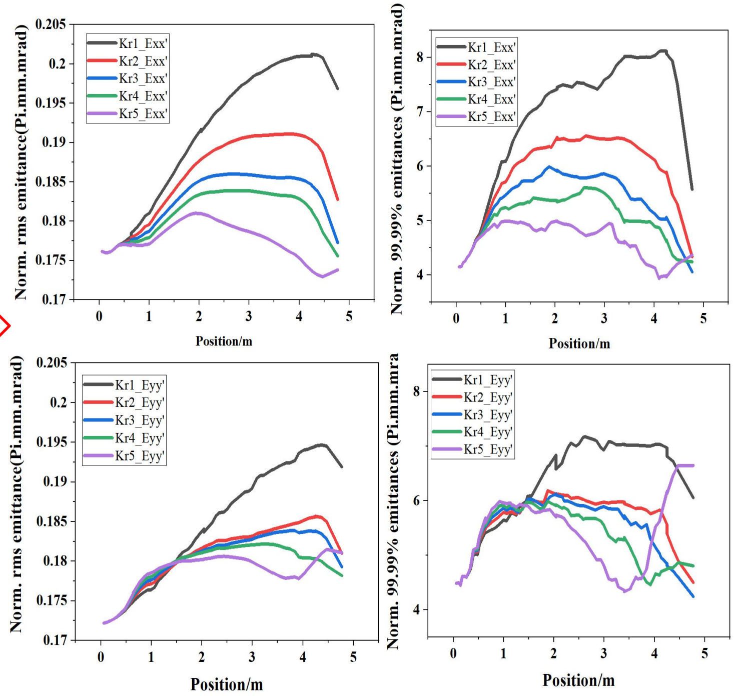
Ref:M.A. Plum, Proceedings of HB2012, Beijing, China

Beam loss control: MEBT design

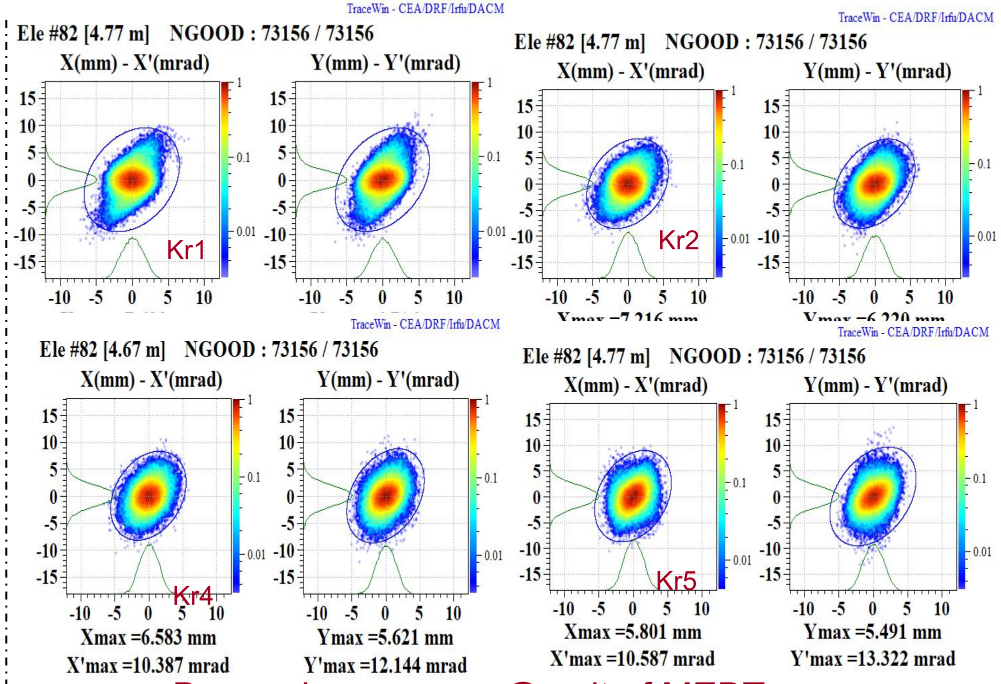


Envelope optimization aiming at emittance growth and avoiding the phase space distortion



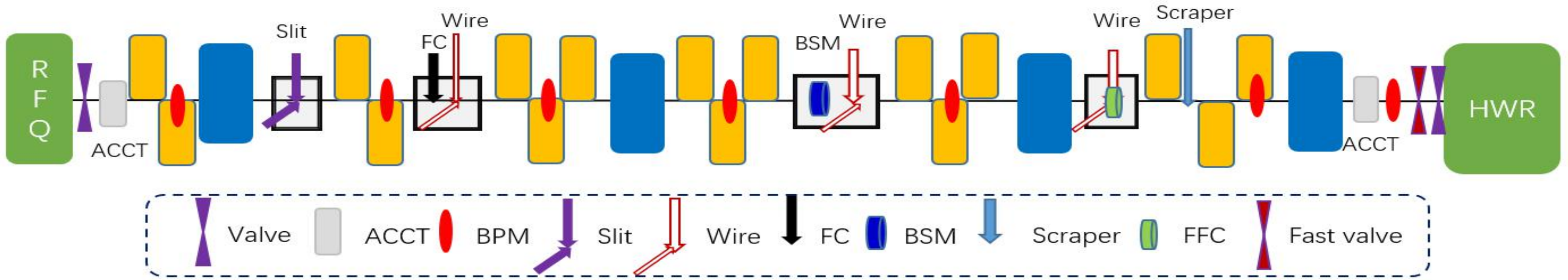


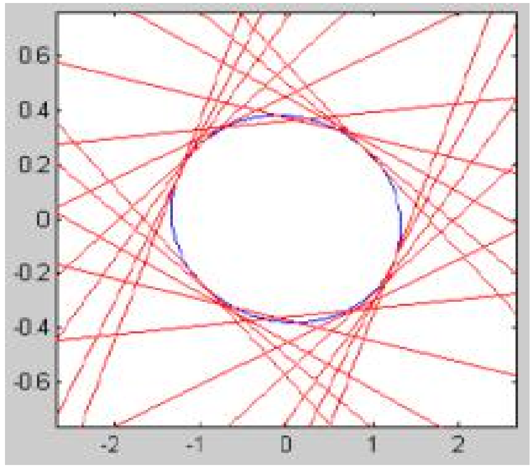
Beam envelope optimization



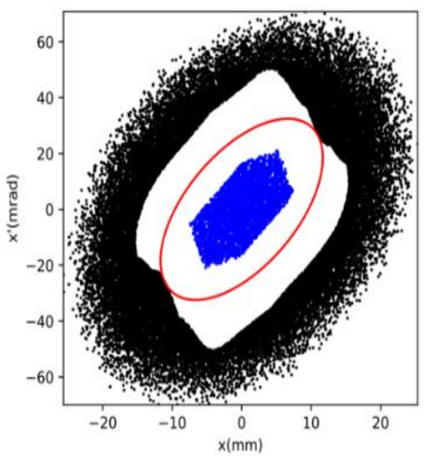
Beam phase space @ exit of MEBT

Beam loss control: MEBT design

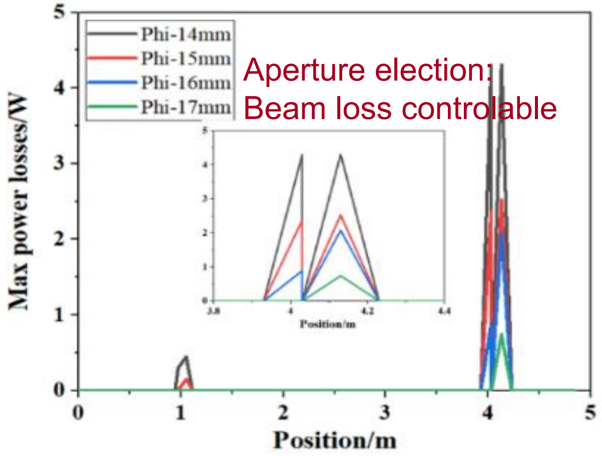




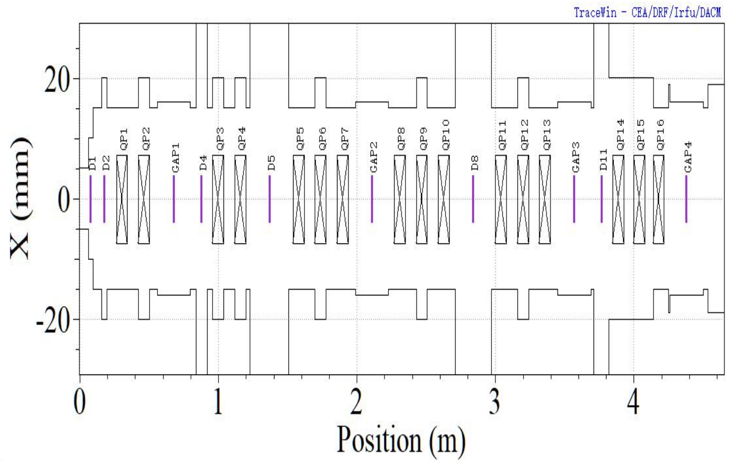
Full space scraping



Acceptance of SC section and MEBT



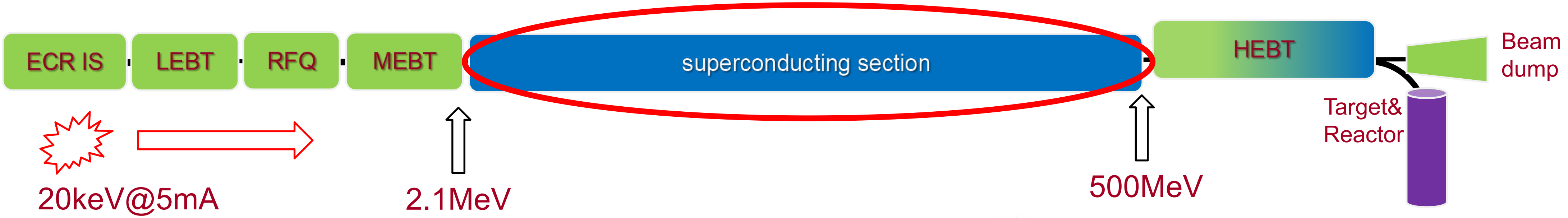
Beam loss @ different aperture



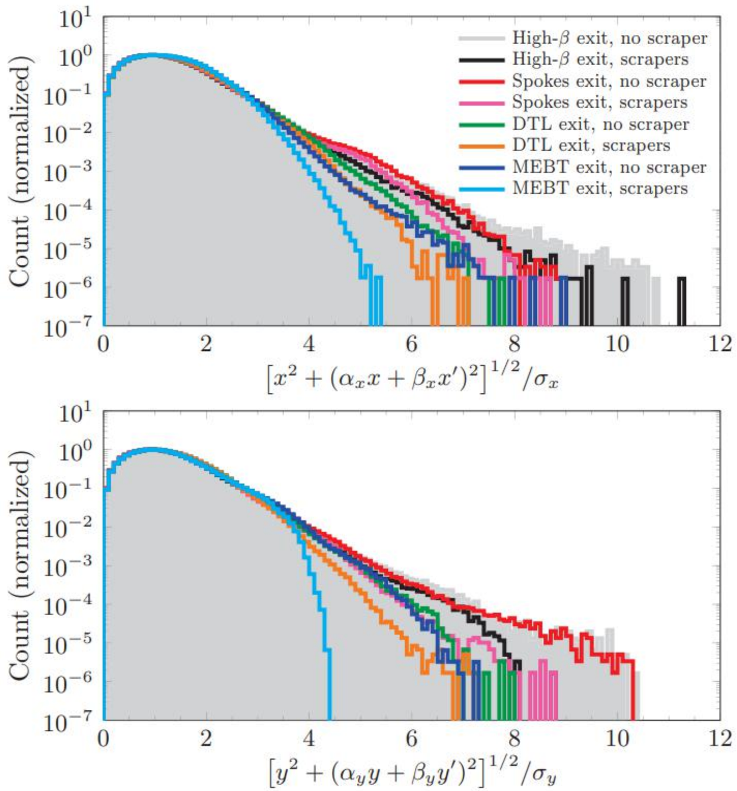
Beam aperture along the MEBT

Smaller acceptance of MEBT than that of SC section is considered to reduce beam loss probibility in the downstream linac. This method can achieve a continual scraping along the MEBT by selecting apropriate beam aperture.

Beam loss control: issue@SC section

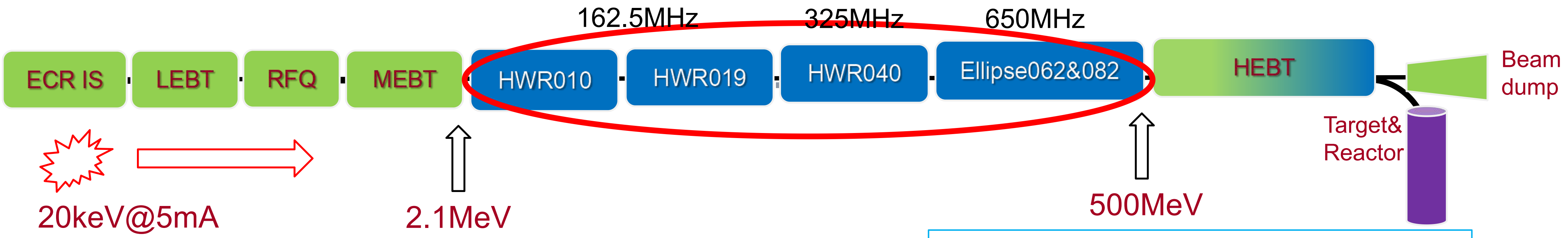


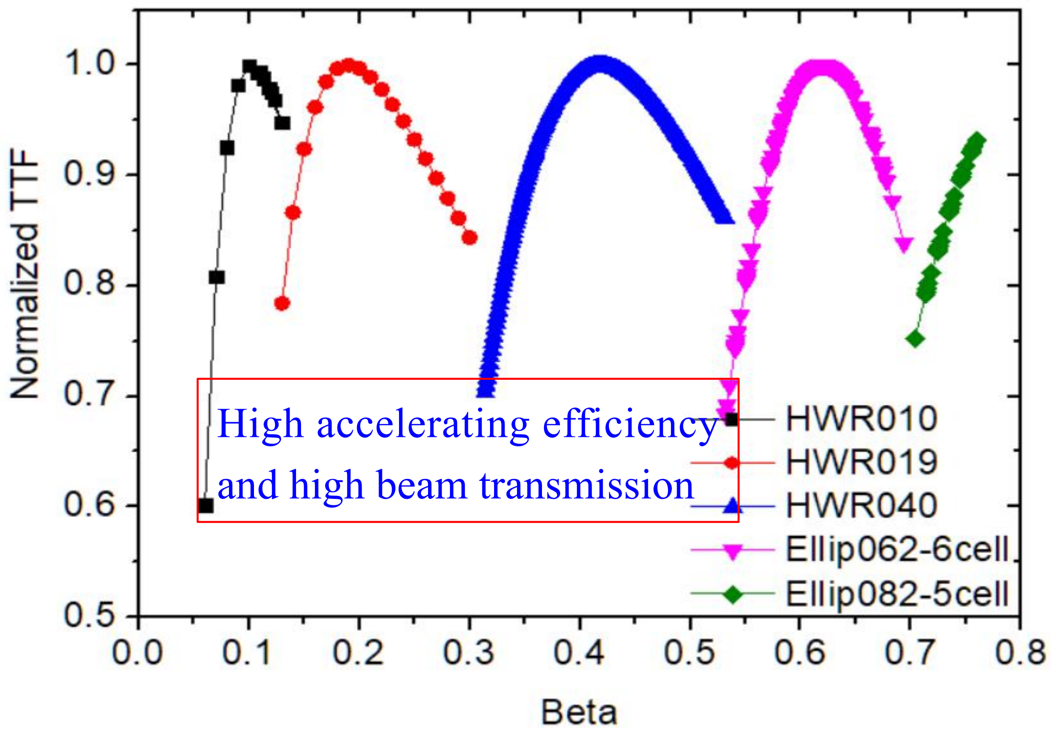
- ☐ **High accelerating efficiency for low cost**
- ☐ **Low beam loss control**
  - ✓ **Lattice optimiaztion & Beam matching** for mitigating halo formation and beam emittance growth
  - ✓ **Beam halo collimation** to reduce the probability of beam loss on SC elements
  - ✓ **Beam loss detection** for high beam availability



Ref:R.Miyamoto, An Ess Linac Collimation Study，HB2014

Beam loss control: SC section design





Parameters of superconducting cavity

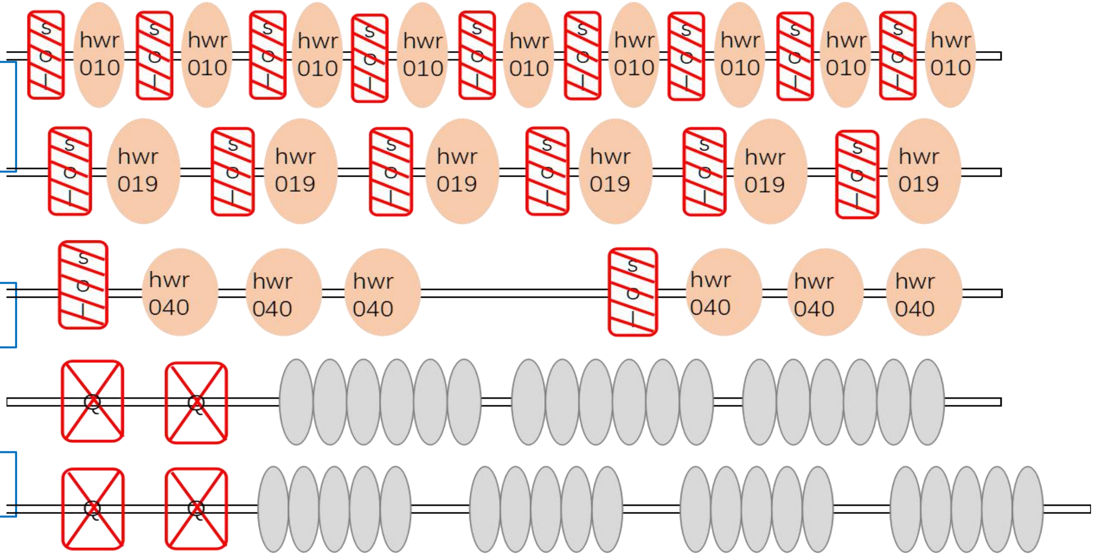
	HWR010	HWR019	HWR040	Ellip062	Ellip082
Frequency (MHz)	162.5	162.5	325	650	650
βopt	0.10	0.19	0.40	0.62	0.82
No. cell	2cell	2cell	2cell	6cell	5cell
Epeak (MV/m)	26	28	29	29	29
No.cavity	9	24	60	40	24
Total No.cavity	157				

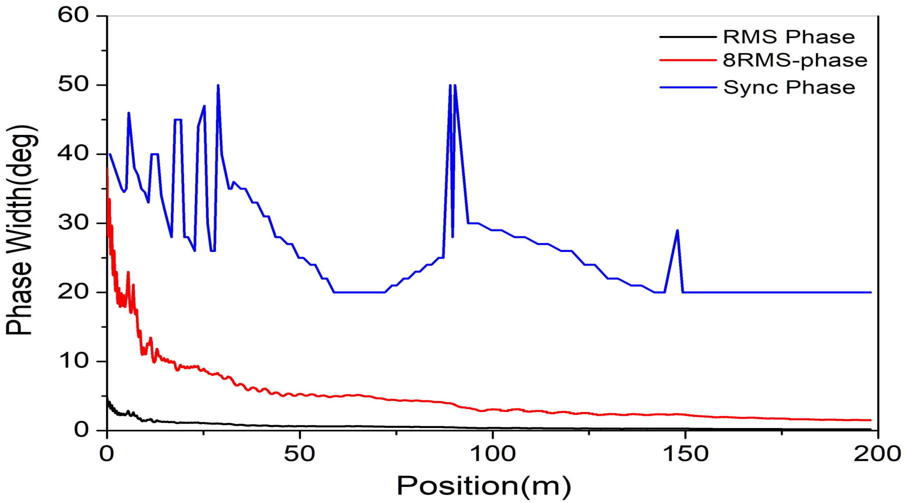
Beam loss control: SC section design

Compact lattice structure & HMR

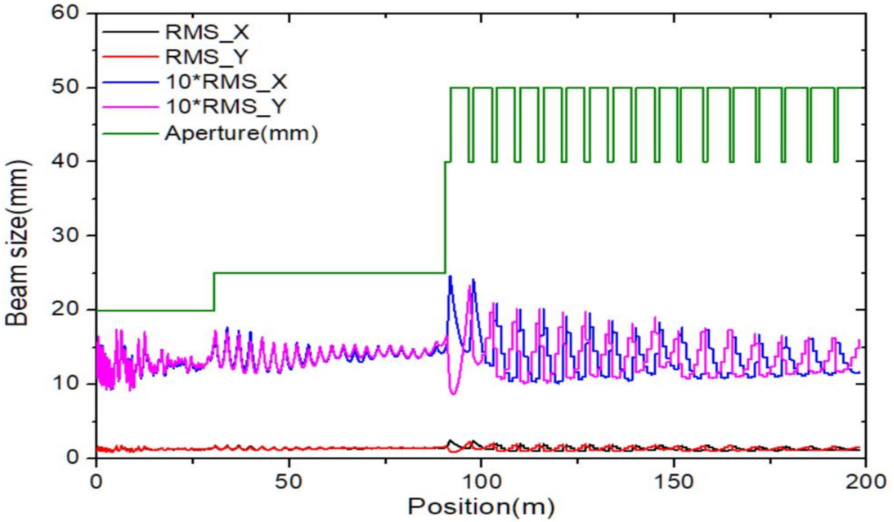
Full period lattice

Full period lattice





Relationship between phase width and sync phase



Relationship between envelope and aperture

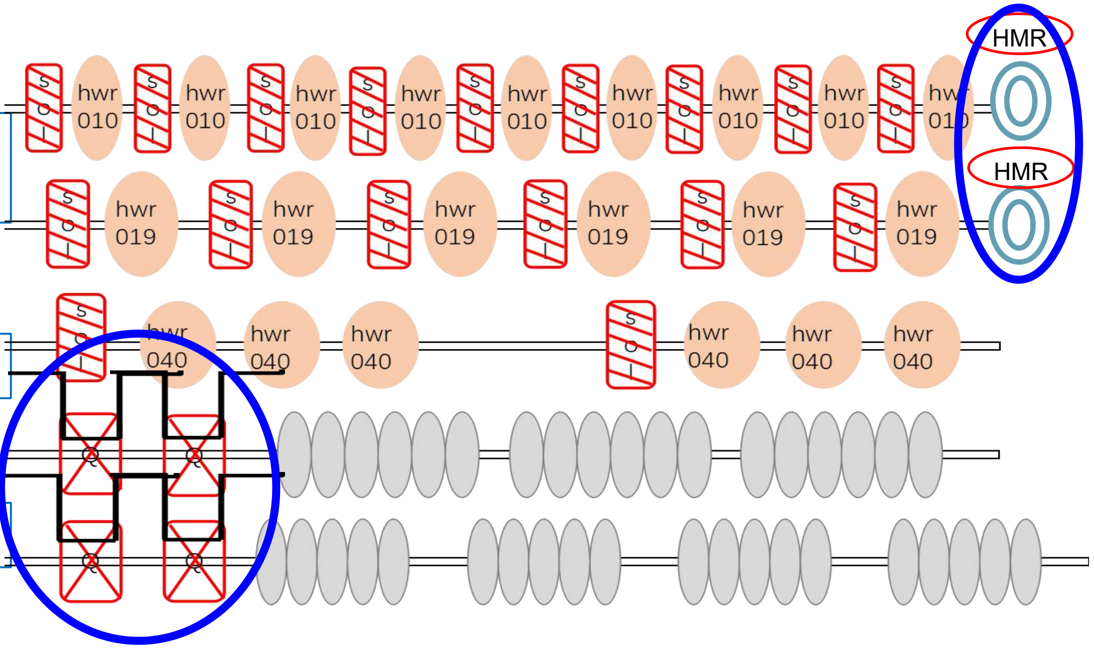
- **Lattice optimiaztion & Beam matching** to avoid beam halo formation
  - Multiple focusing periods per cryomodule to reduce space charge effects at low/medium energy SC segment;
  - one focusing period per cryomodule to reduce the impact of mismatch at high energy SC segment

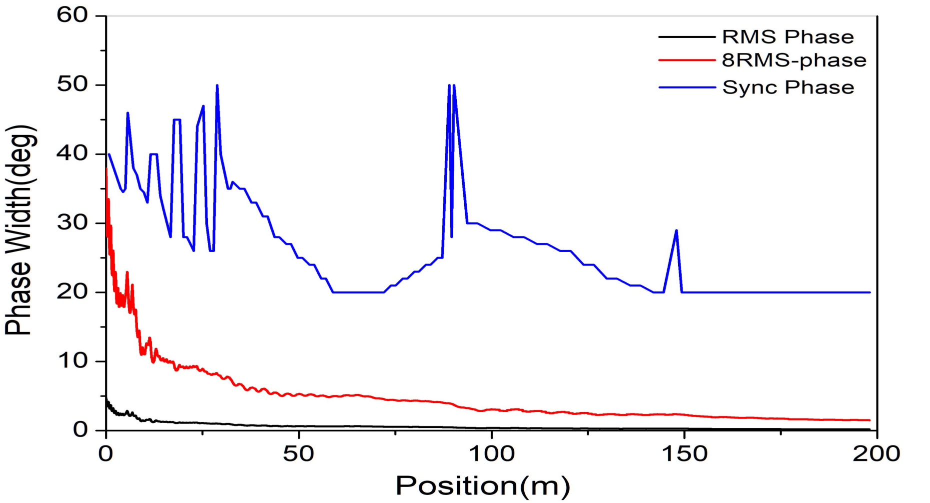
Beam loss control: SC section design

Compact lattice structure & HMR

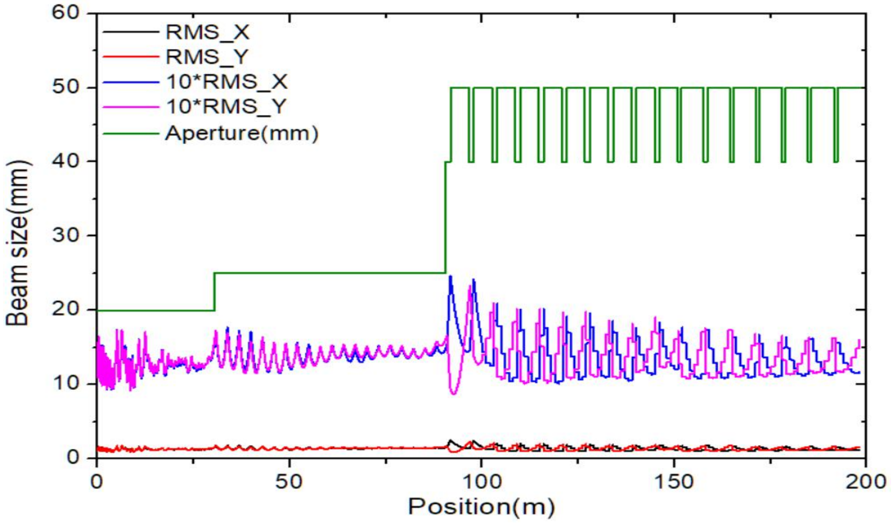
Full period lattice

Full period lattice





Relationship between phase width and sync phase

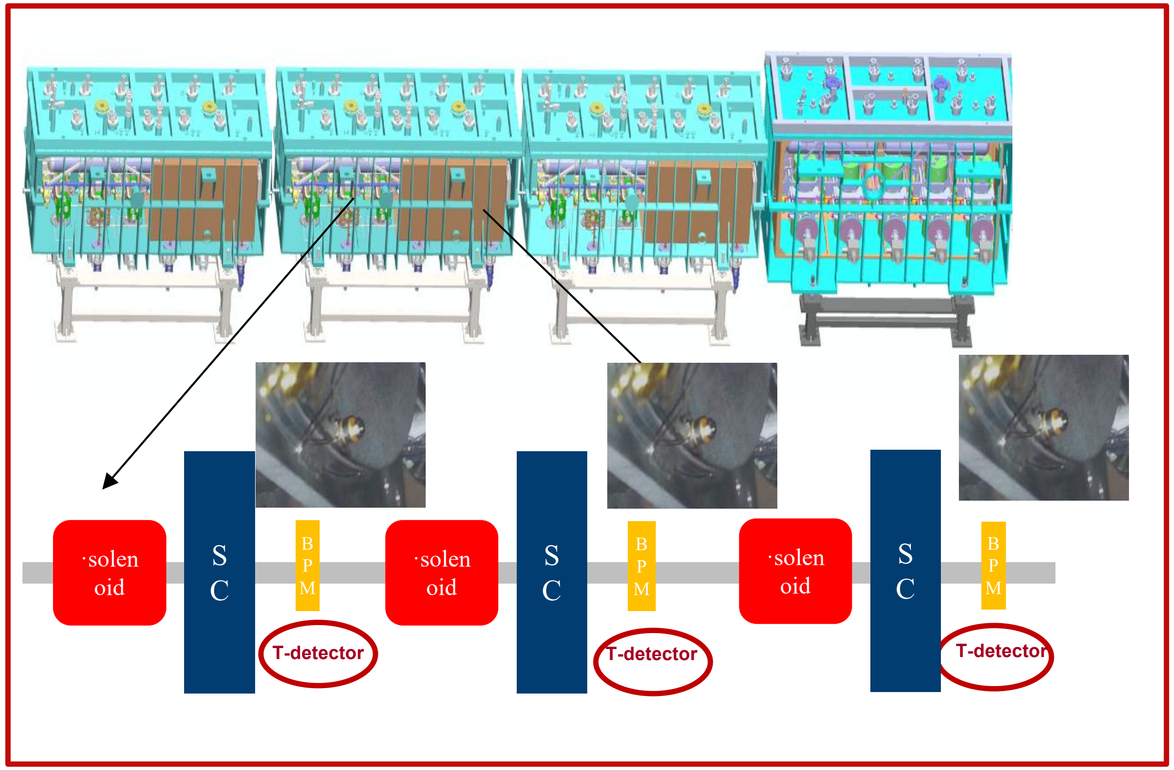


Relationship between envelope and aperture

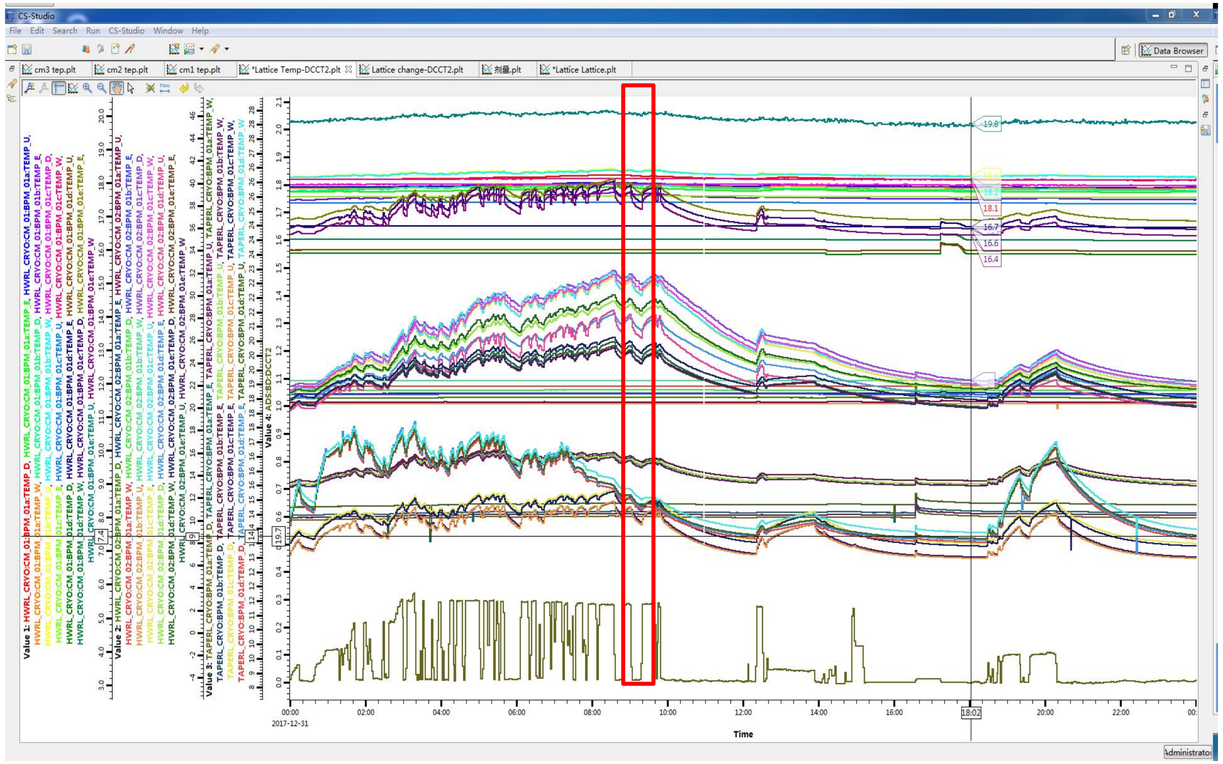
- **Lattice optimiaztion &Beam matching** to avoid beam halo formation
  - Multiple focusing periods per cryomodule to reduce space charge effects at low/medium energy SC segment;
  - one focusing period per cryomodule to reduce the impact of mismatch at high energy SC segment
- **Beam halo collimation:** HMR for beam halo scraping @ low/medium energy part; smaller RT magnet diameter for halo scraping @ high energy part

Beam loss control: Beam loss detection

- Beam loss detection @ low energy based on temperature detectors and HMRs

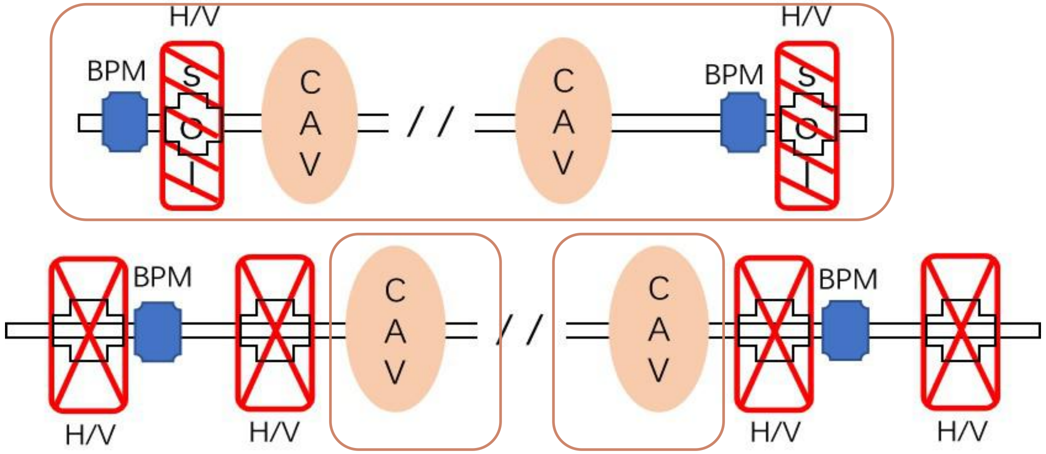


Four T-detectors located on the flange of cold BPMs to detect slow beam loss due to beam halo or off center

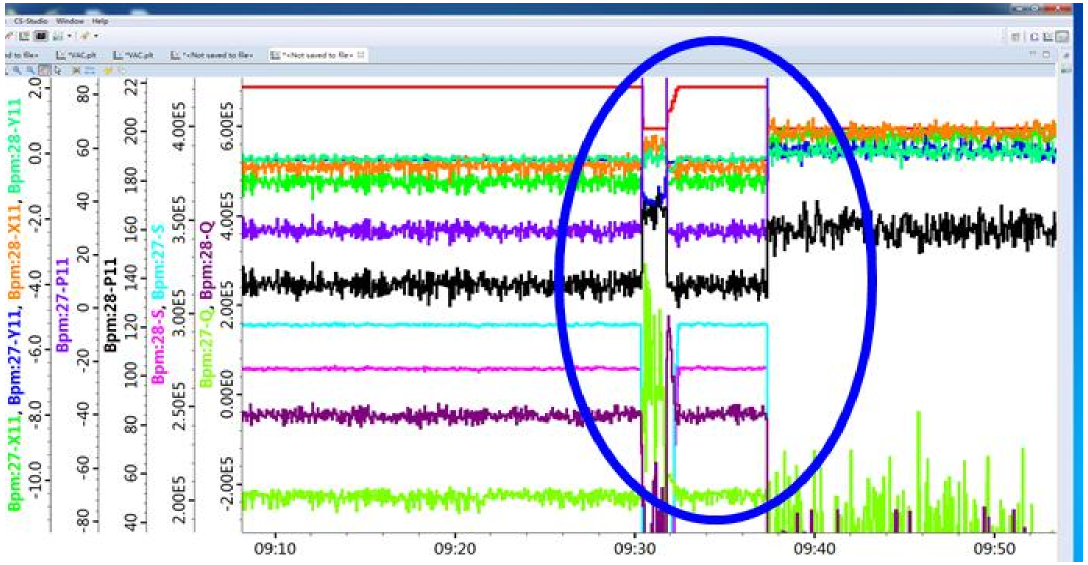


The T-detectors effectively indicate the loss during high beam power commissioning

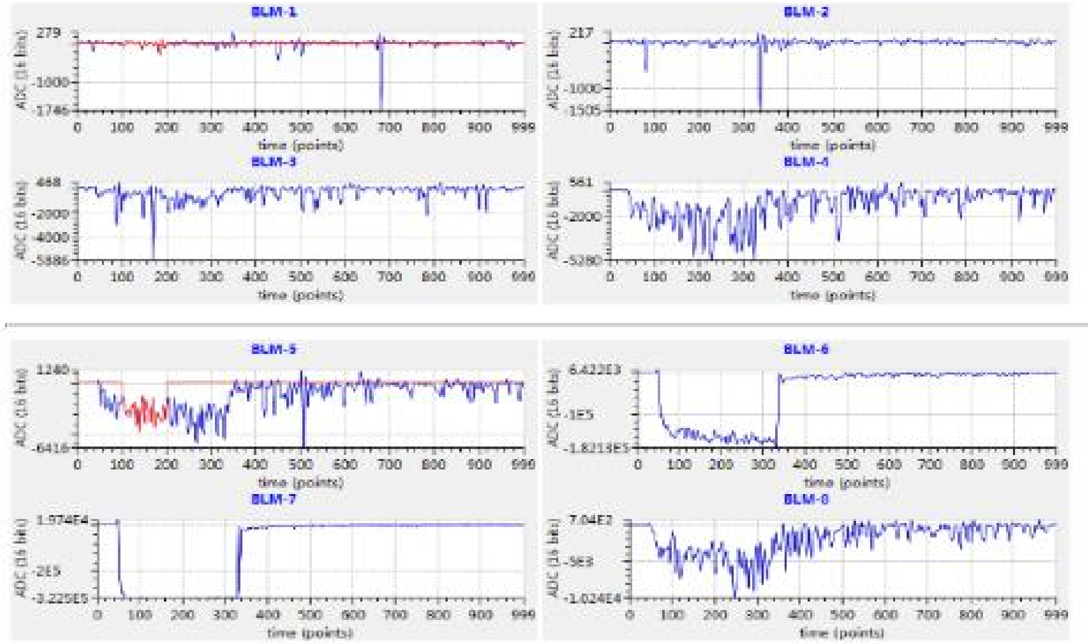
Beam loss control: Beam loss detection



- Beam loss detection @ high energy based on BLM

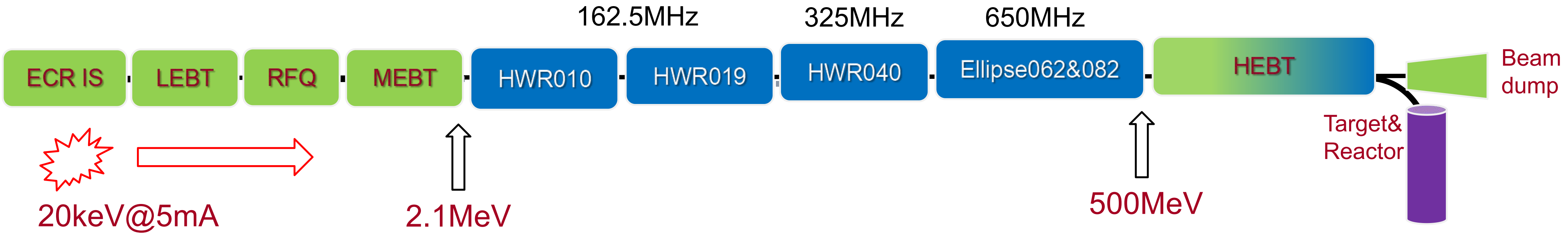


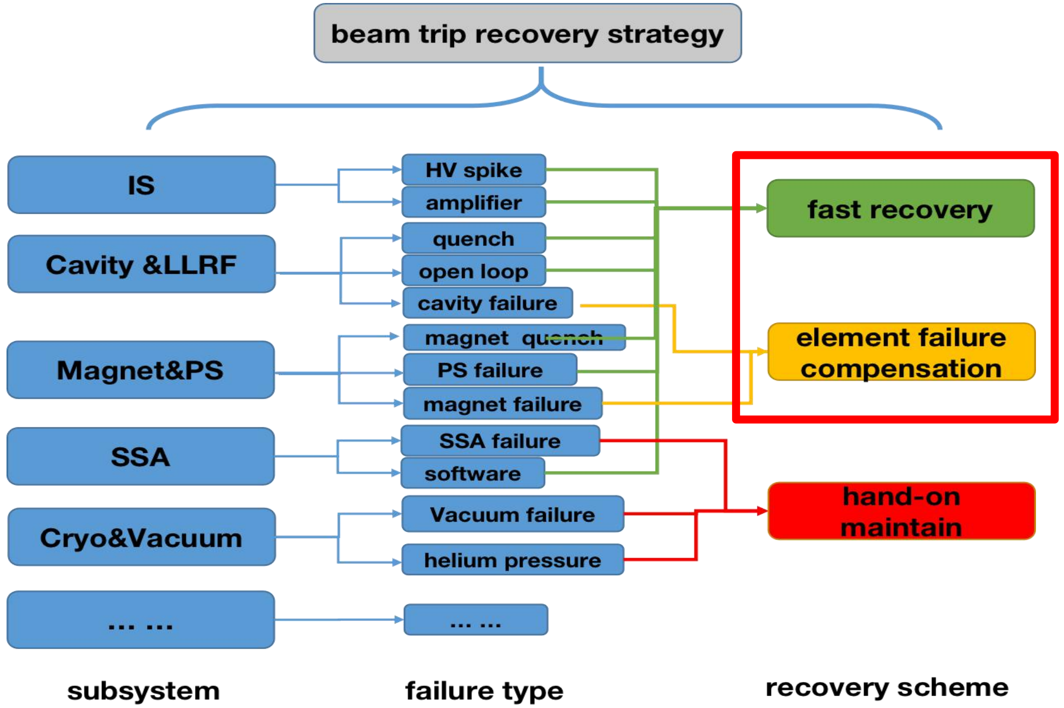
Beam state signal based on BPMs @CAFe



Beam loss signal based on BLM

Beam recovery for high availability





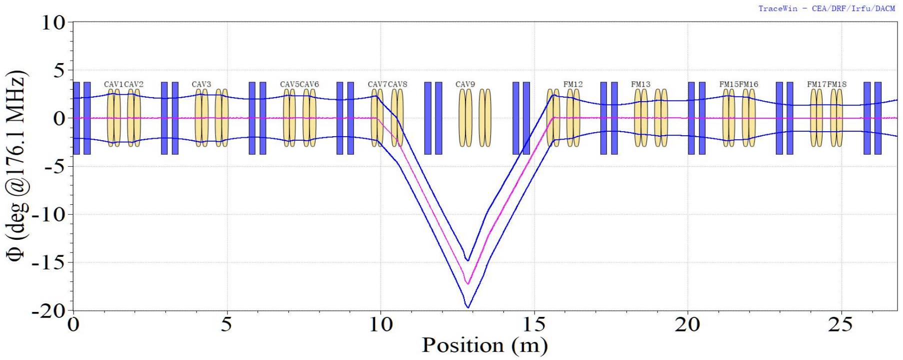
Beam Trip Requirements of Industrial Scale ADS

Beam Trip Duration	Industrial Scale Transmutation	Remarks
T<1sec	<25000	Target window lifetime
1sec<T<10sec	<2500	Fatigue failure of fuel cladding
10sec<T<5min	<2500	Fatigue failure of inner barrel and reactor vessel
T>5min	<50	System Availability

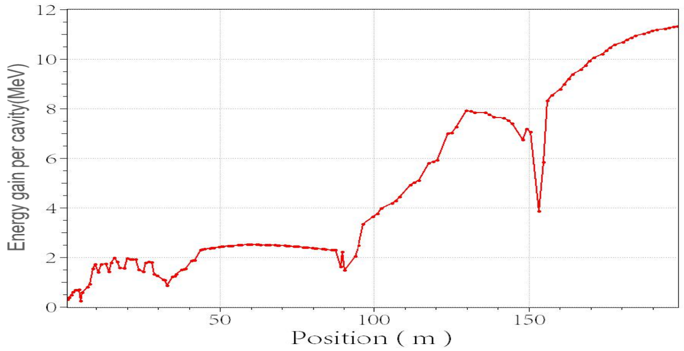
Element failure compensation

Rematch twiss parameters to avoid beam loss at the location where the failure occurred by adjusting the neighboring cavities and magnets of the failure cavity

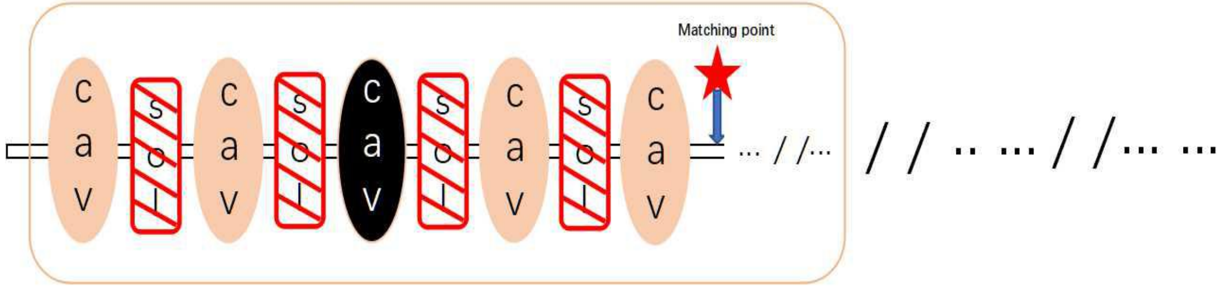
It is more effective to achieve energy compensation by cavities in the high energy part because of the greater acceleration capability of the high beta cavity

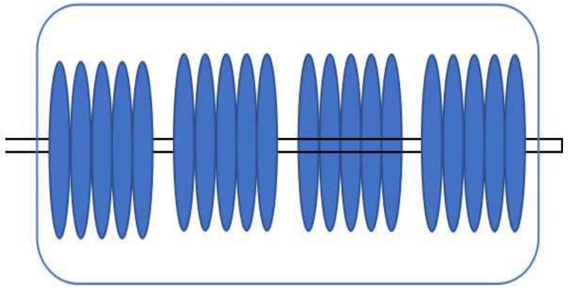


Twiss parameters matching



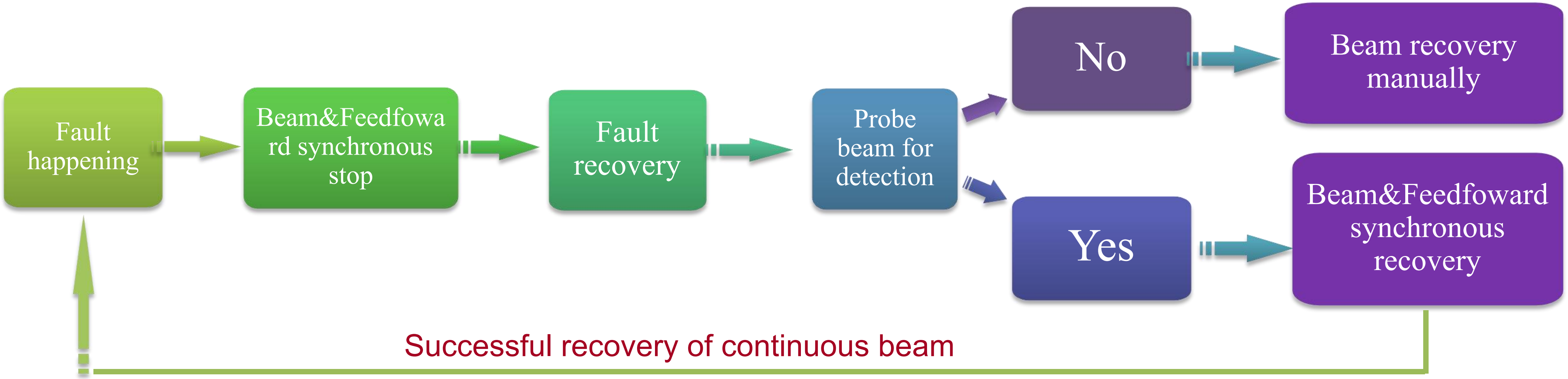
Energy compensation

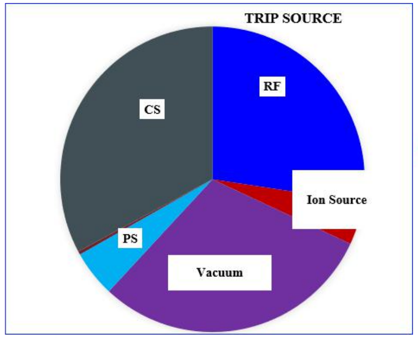


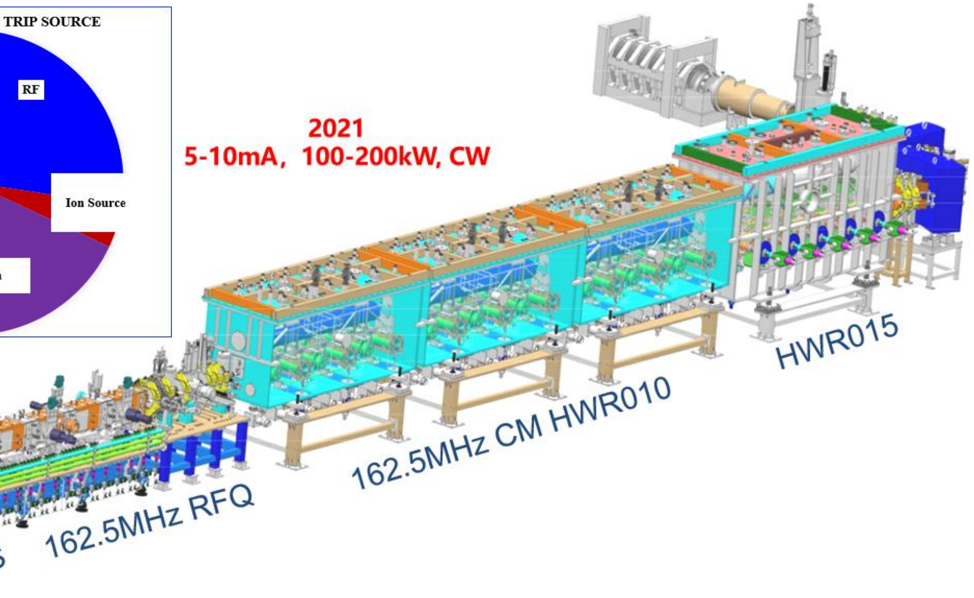


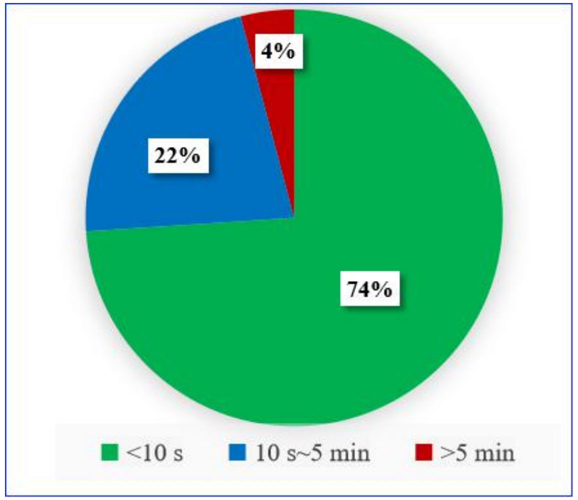
Hybrid fault compensation scheme based on physical characteristics-Matching compensation and energy compensation are considered separately.

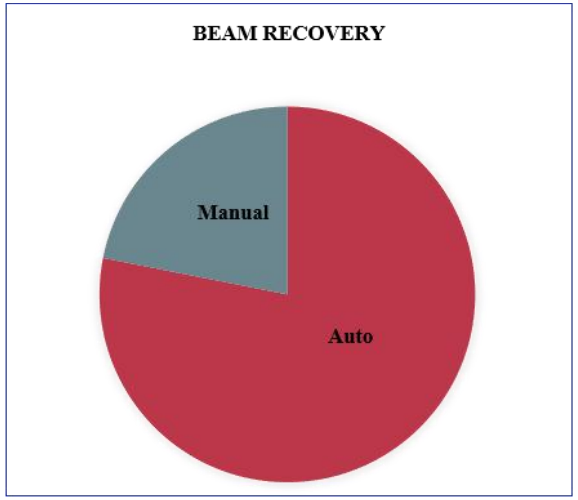
Fast recovery











Summary

- The CiADS is expected to have the first 500 MeV beam acceleration in 2027.
- The physics design of sc-linac for CiADS has been done facing low beam loss and high availability.
- Beam loss detect and machine protect have been considered based on beam instrumentation
- Fast beam recovery scheme was proposed and verified in improving the availability of operation in CAFe.
- Beam physics and technology study for high beam availability is on going

Thanks for your attention