High Intensity Aspects of the CSNS Accelerators

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CSNS
CHINESE ACADEMY OF SCIENCES

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Main topics

- Introduction to CSNS project
- Space charge effects in CSNS accelerators
  - Linac
  - LRBT
  - RCS
- Beam loss and collimation
  - Beam loss control in linac
  - Halo collimation in LRBT
  - Beam loss and collimation in RCS
- Beam spot uniformization at the target
- Other high intensity aspects
- Conclusions

Introduction to CSNS Project

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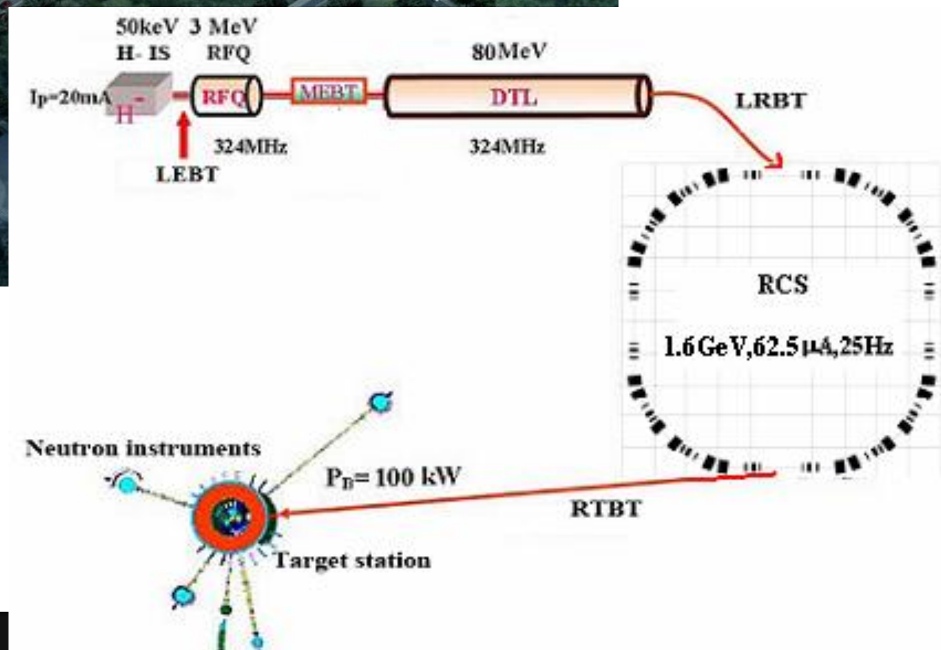
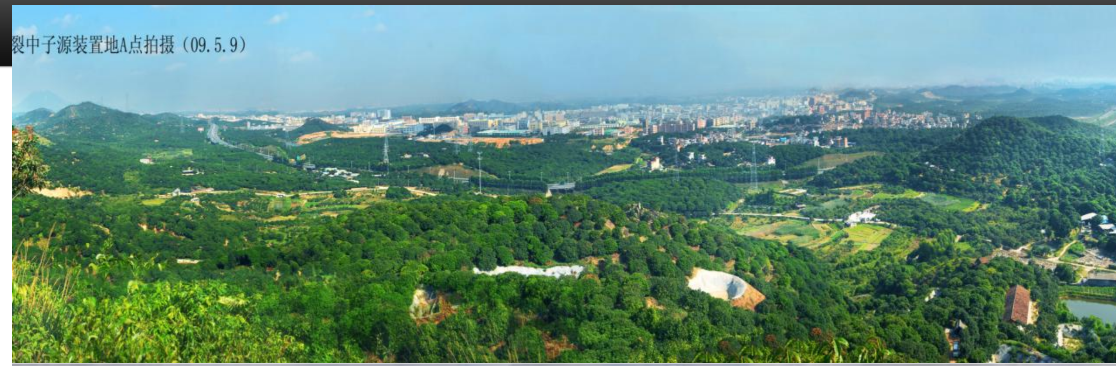

50keV 3 MeV
H- IS RFQ
80MeV
Ip=20mA
RFQ
MEBT
DTL
LRBT
324MHz
324MHz
LEBT
RCS
1.6GeV,62.5μA,25Hz
Neutron instruments
P_B= 100 kW
RTBT
Target station

CSNS Status

- CSNS is waiting for the approval of feasibility study (delayed as we asked to increase the budget from 1.4 BCNY to 1.7 BCNY recently, not including the contribution of local government)
- Land preparation is under way
- R&D and prototyping are going
- Expect to start construction in early next year



RCS location

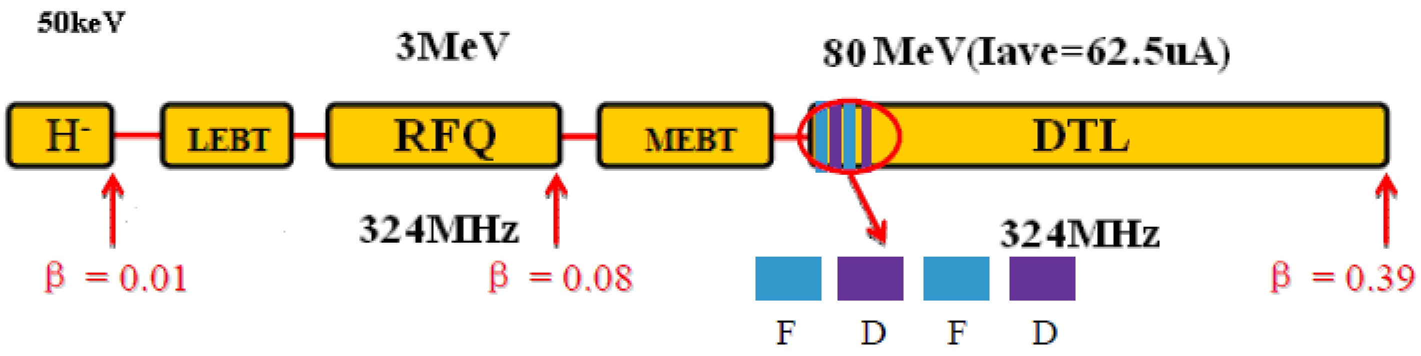
CSNS Main Parameters

Phase	I	II	II' or III
Beam power on target [kW]	100	200	500
Beam energy on target [GeV]	1.6	1.6	1.6
Ave. beam current [μA]	63	125	315
Pulse repetition rate [Hz]	25	25	25
Protons per pulse [10^{13}]	1.6	3.1	7.8
Linac energy [MeV]	80	132	250
Linac type	DTL	DTL	DTL+SCL
Target number	1	1	1 or 2
Target material	Tungsten		
Moderators	H_2O (300K), H_2(20K, coupled & non)		
Number of spectrometers	3+1	20+1	>=20

Space charge effects in CSNS accelerators

Space charge effects in the linac

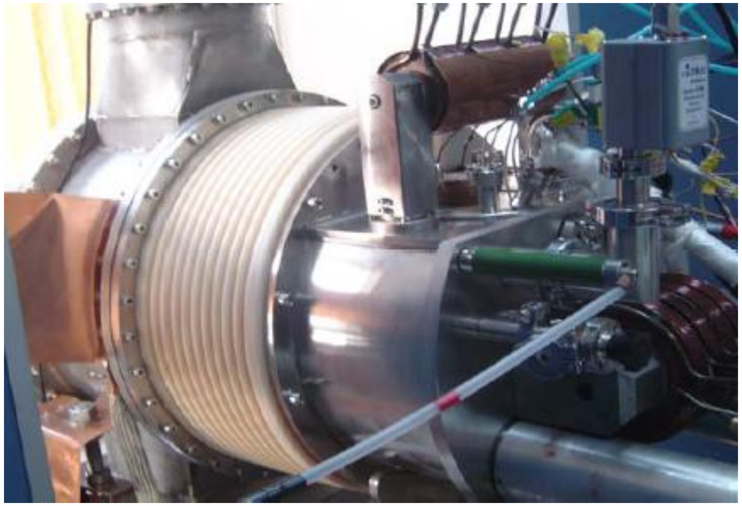
- CSNS linac scheme and main parameters

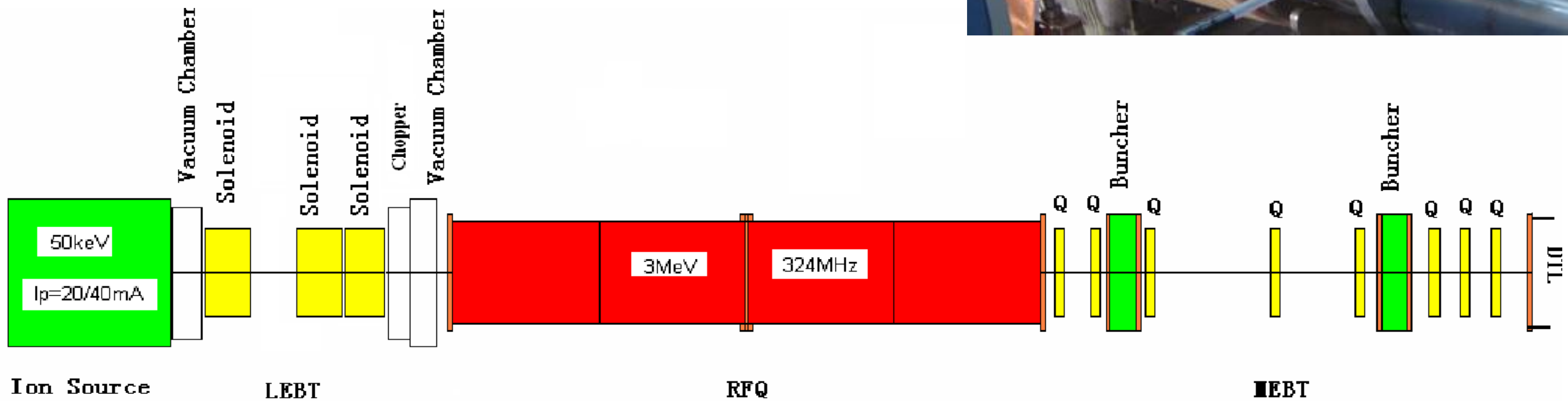


	Ion Source	RFQ	DTL
Input Energy（MeV)		0.05	3.0
Output Energy(MeV)	0.05	3.0	80/132
Pulse Current (mA)	20/40	20/40	15/30
RF frequency (MHz)		324	324
Chop rate (%)		50	50
Duty factor (%)	1.3	1.05	1.05
Repetition rate (Hz)	25	25	25

Front-end

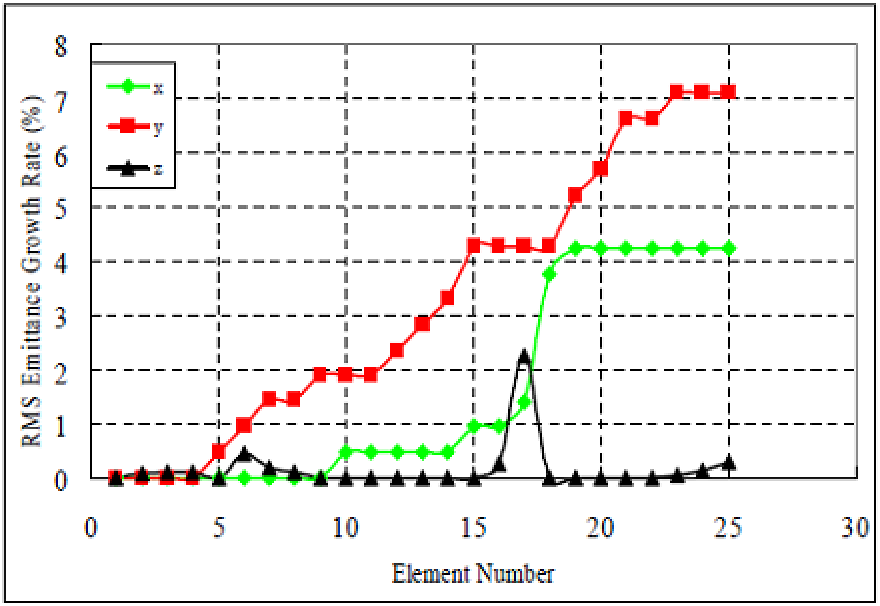
- **Front-end scheme: Penning surface H- ion source (same as the ISIS source), magnetic LEBT (3 solenoids), electrical chopping at LEBT end, four-vane RFQ, MEBT with bunchers**
- **Residual-gas neutralization in LEBT except the last part (chopping)**
- **Matching for non-symmetric beam from the source.**
  - Study show that 4 mini-quads are needed when space charge included (e.g., 90% neutralization)



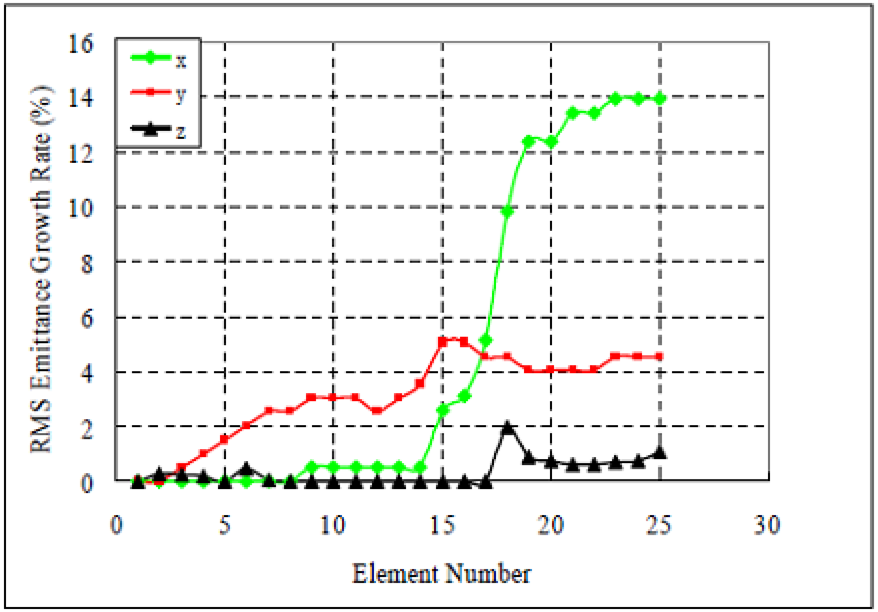


- The RFQ is designed by following the success of ADS-RFQ (four-vane, 3.5 MeV, 352MHz, 7% duty factor)
  - It can accelerate high intensity beam until 50 mA with good transmission efficiency (~93%).
- MEBT has been shortened by taking away the choppers
  - Shorter is better by following the comments of ATAC review
  - Critical section for emittance growth due to the space charge effects.
  - Non-adiabatic change of the focusing structure
  - Adjustability for different beam intensity

- **Macro-particle simulations (PARMILA) for MEBT**
  - **I=20mA: rms emittance growths: 7.1%, 4.3% and 0.3% for x,y,z**
  - **I=40mA: rms emittance growths: 14%, 4.5% and 1.1% for x,y,z**



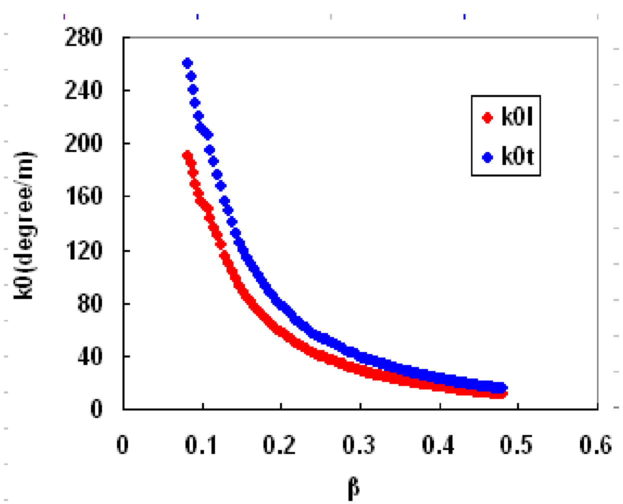
I=20mA

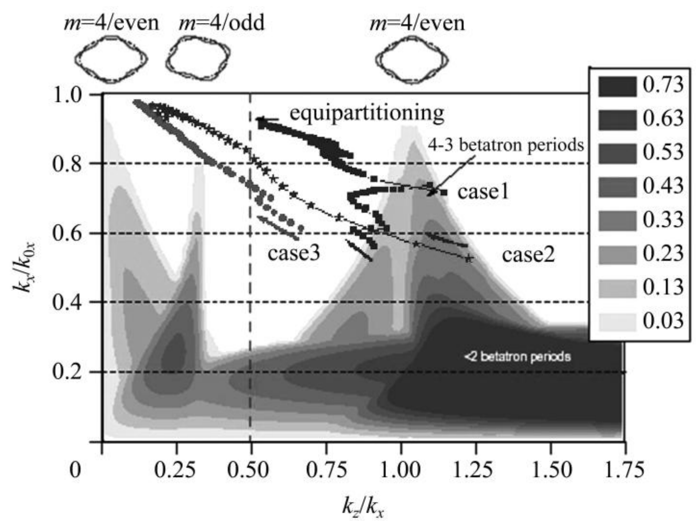


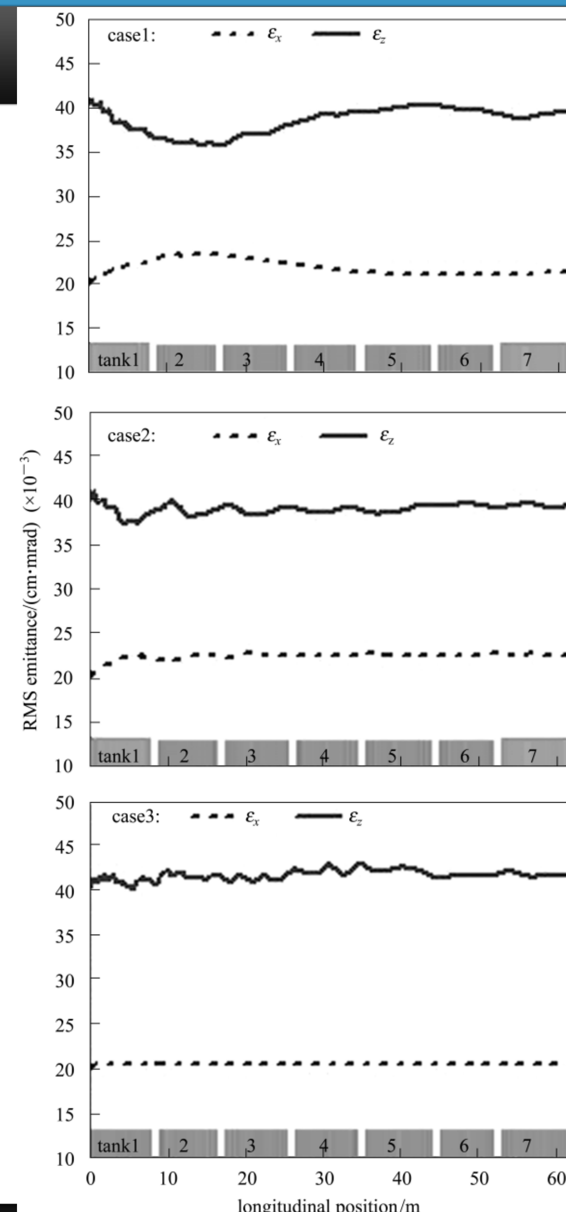
I=40mA

Space charge effects in DTL

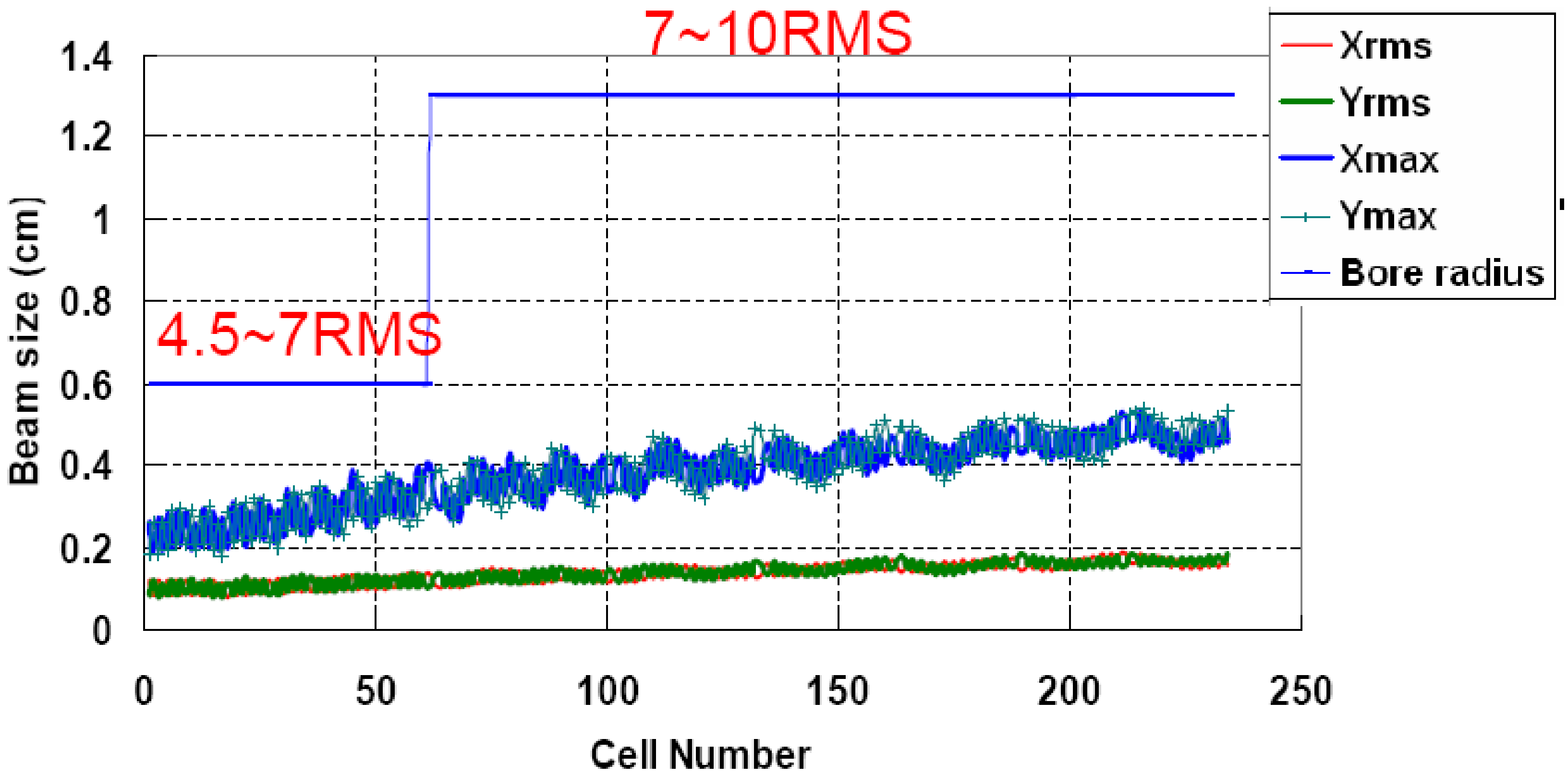
- **Strong space charge exists in DTL, especially in the first tank. Strong electromagnetic quadrupoles in drift-tubes with an FD lattice give sufficient focusing.**
- **To avoid emittance exchange between the transverse and longitudinal, equipartitioning method is used to choose the tunes.**







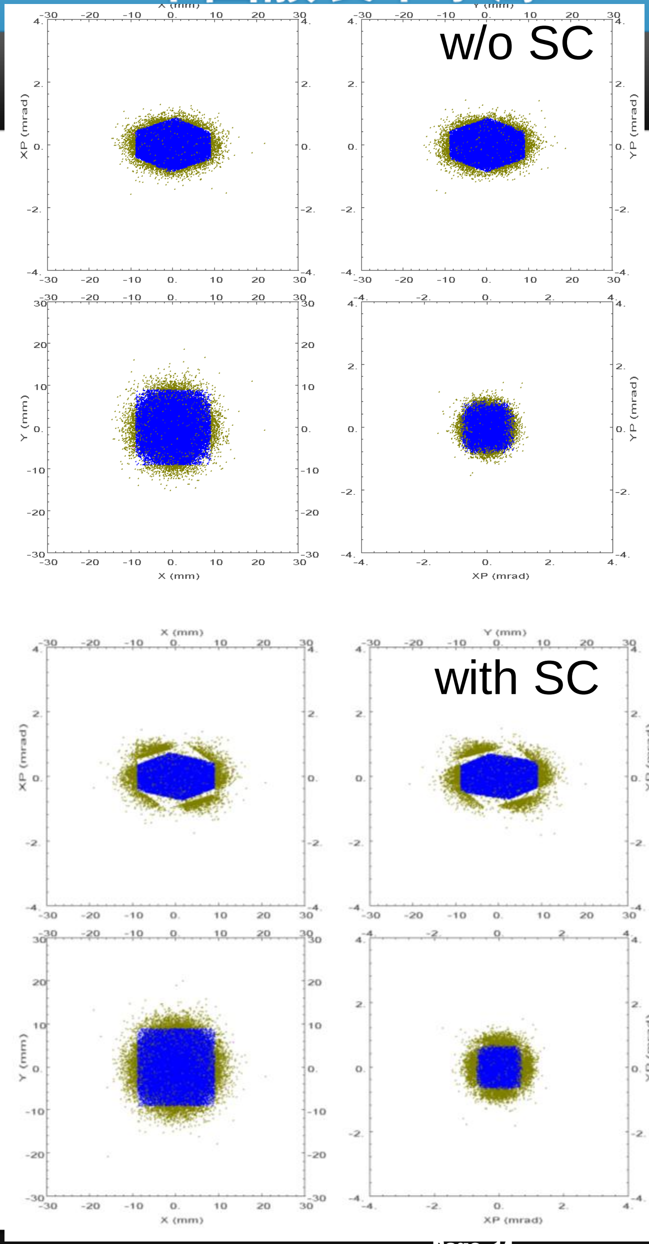
PARMILA simulations



RMS and total beam size

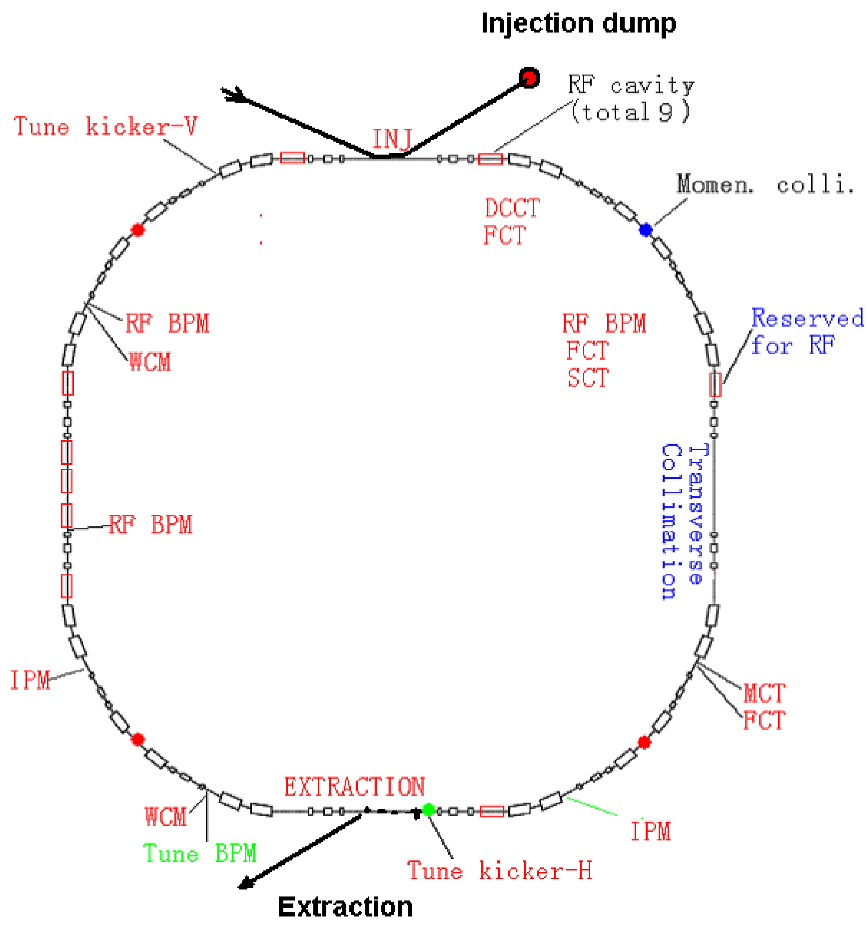
Space charge effects in LRBT

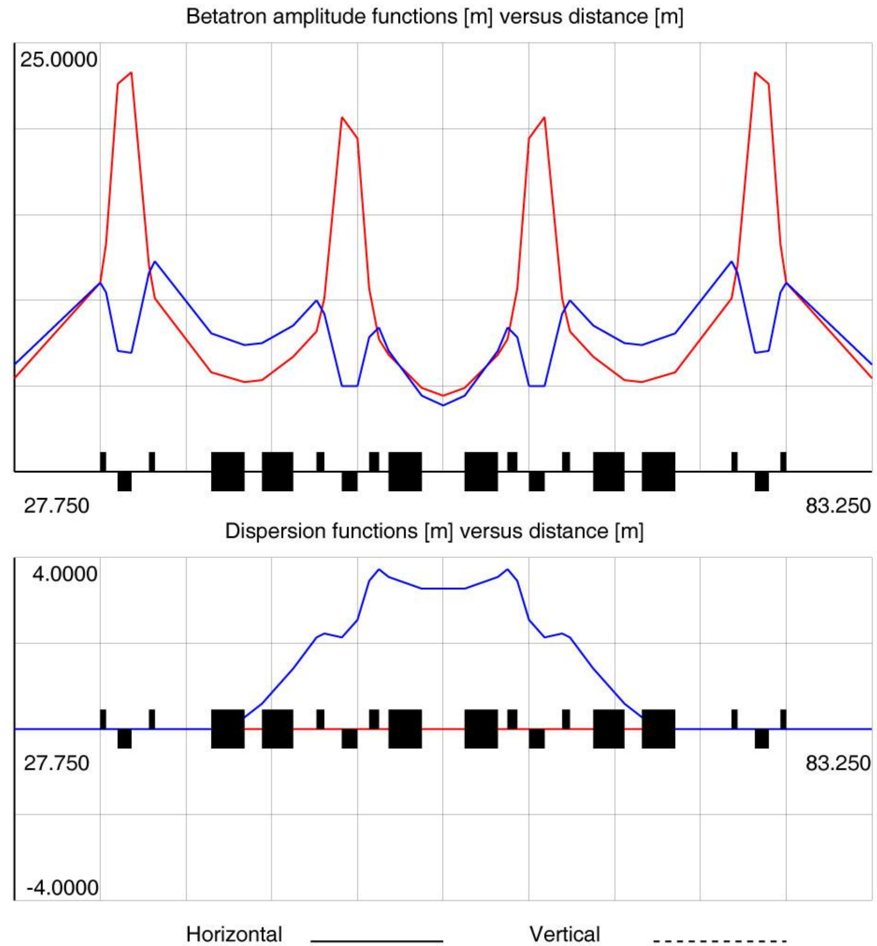
- **Important, especially at LRBT entrance where beam is much bunched**
  - **Transverse matching section adapted to beam intensity**
- **Debunching leads to higher momentum spread➔ a debuncher needed**
- **Protons from scraped H- halo are focused by the main beam**
  - **After linear SC compensation: H- with 60° phase advance; H+ larger**
- **Dispersion matching in achromatic bending section**



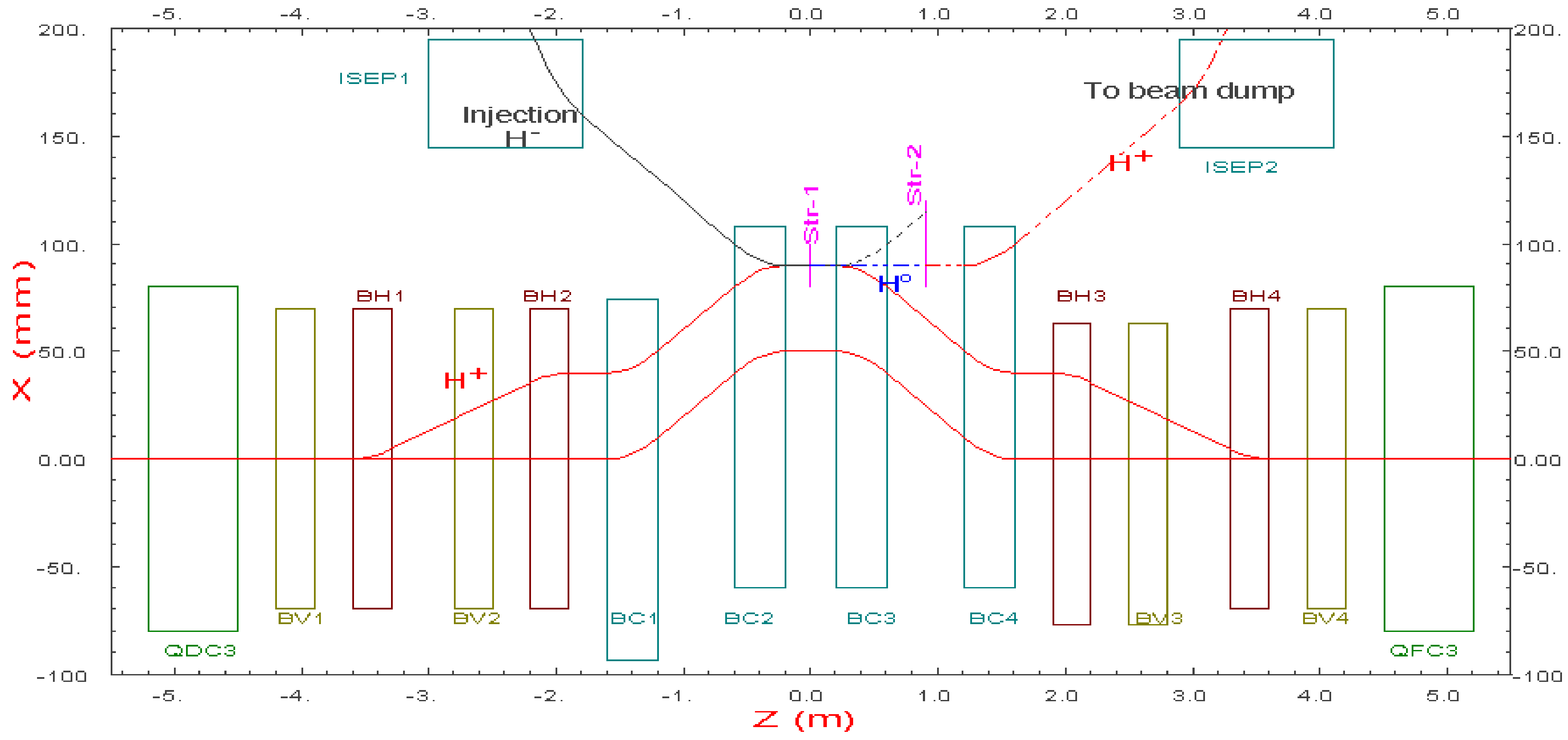
Space charge effect in RCS

- RCS lattice: four-fold, all triplet cells, separate function long straights





RCS Injection Layout



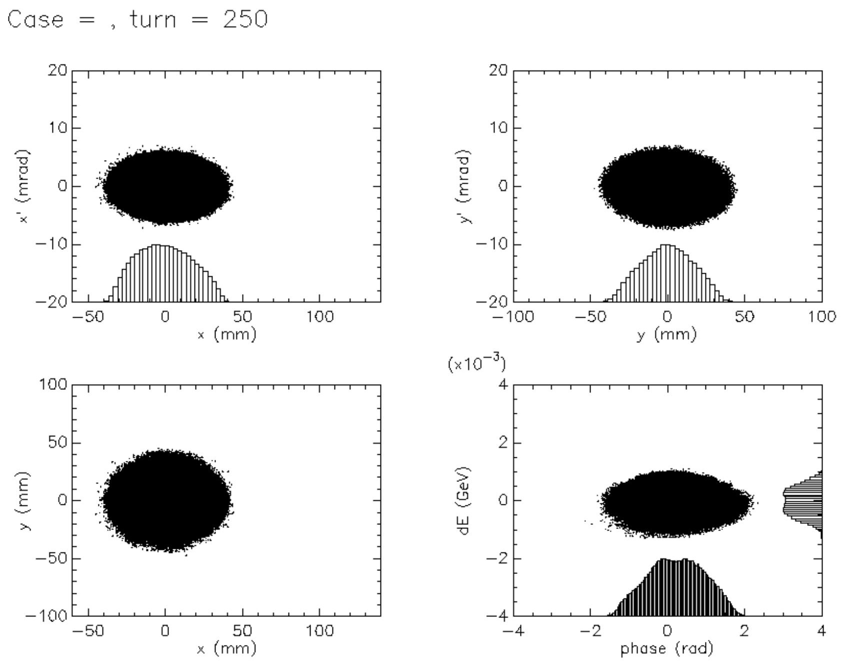
BC1~4: DC Chicane magnets; BH1~4: Horizontal painting magnets; BV1~4: Vertical painting magnets

3D simulations of space charge effects in RCS

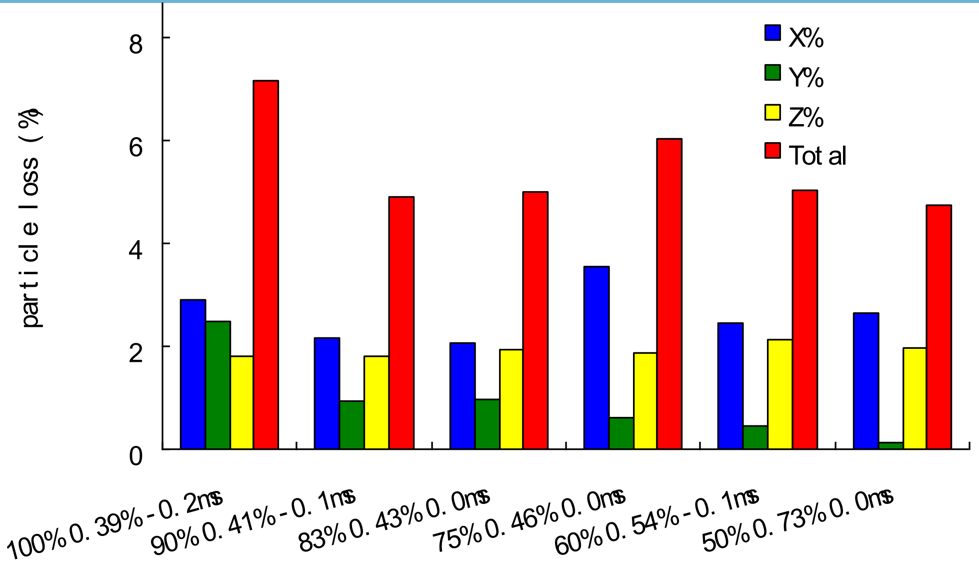
S. Wang's talk (WE01A03)

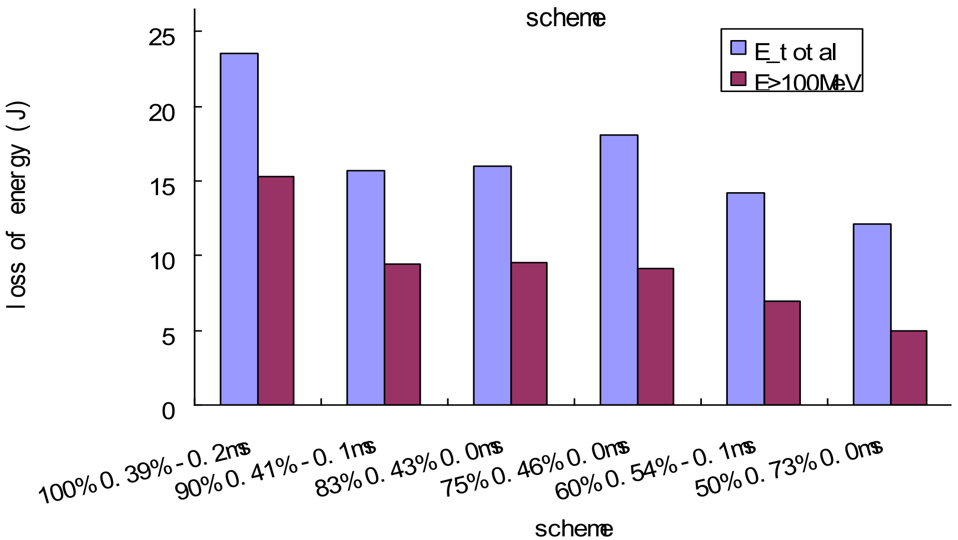
- **Injection (transverse)**
  - Using 3D ORBIT simulations including space charge
  - Focusing on: distribution uniformity, emittance blowup and foil traversal
  - Different working points
  - Correlated and anti-correlated painting schemes
  - Linac peak current dependence
- **Injection (longitudinal)**
  - Chopping rate dependence
  - Longitudinal painting (only with momentum offset)
- **RF capture and initial acceleration**
  - RF voltage curve dependence
  - Trade-off between transverse and longitudinal beam losses

Some simulation results



Beam distribution in phase space after injection (anti-correlated painting, 50% chopping, I=15 mA)

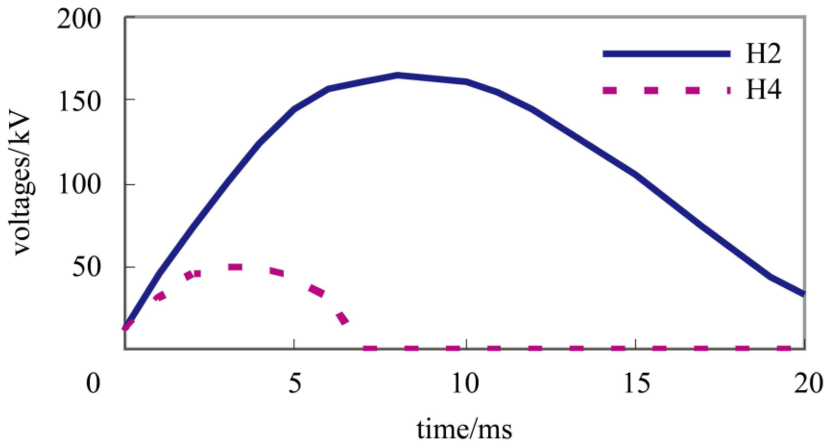


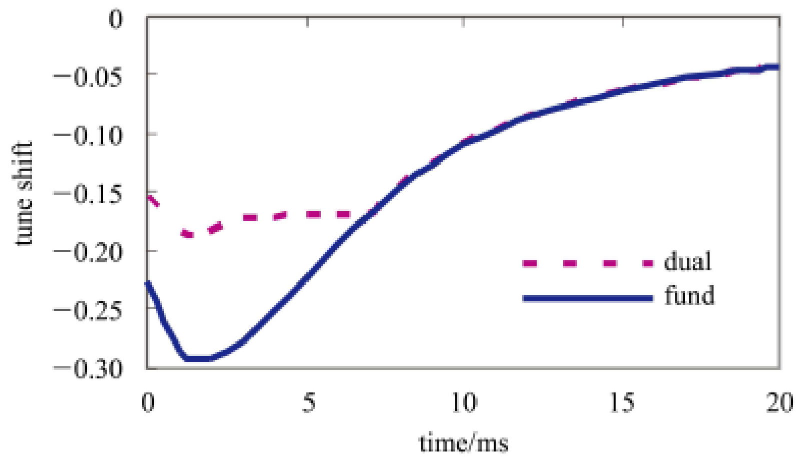


Total beam loss rate - 3D simulation results with different injection schemes (Chopping factor: 100-50%; off-momentum; negative time)

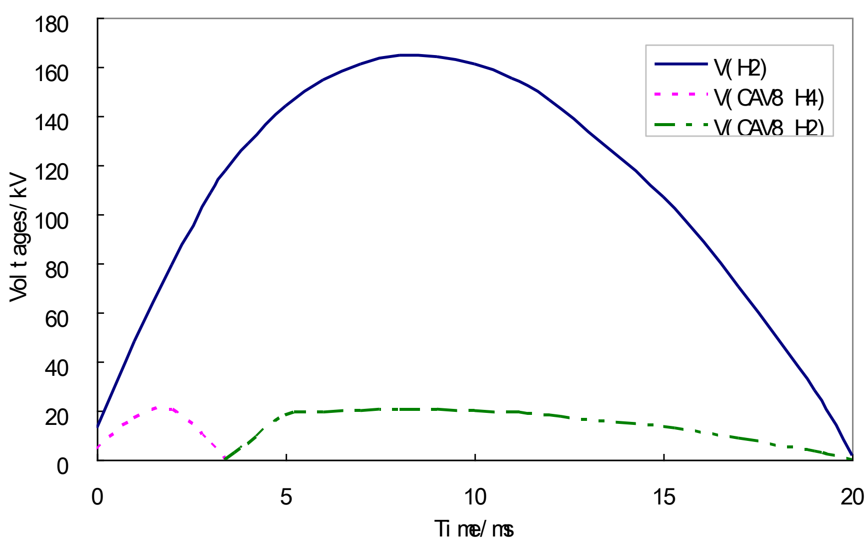
In case of dual RF acceleration

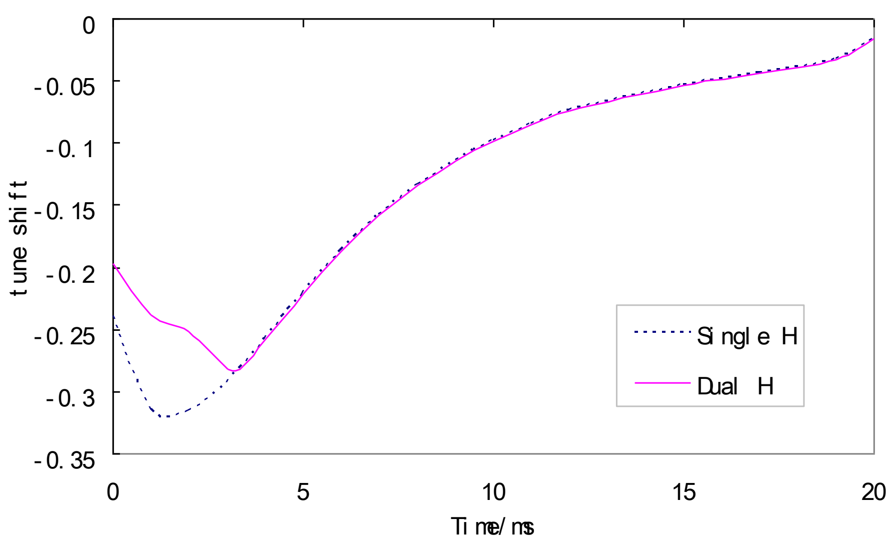
- Higher harmonic (H4) RF cavities added at CSNS-II to compose a dual RF system to alleviate space charge effects
  - Larger bunching factor in first milliseconds
  - More uniform distribution in the longitudinal dimension





- **At CSNS-I, the operation mode with one of the eight RF cavities working at H4 in the first 3~5 ms and then gradually changed into H2 is under study.**
  - **Beam loading factor in the transition period**

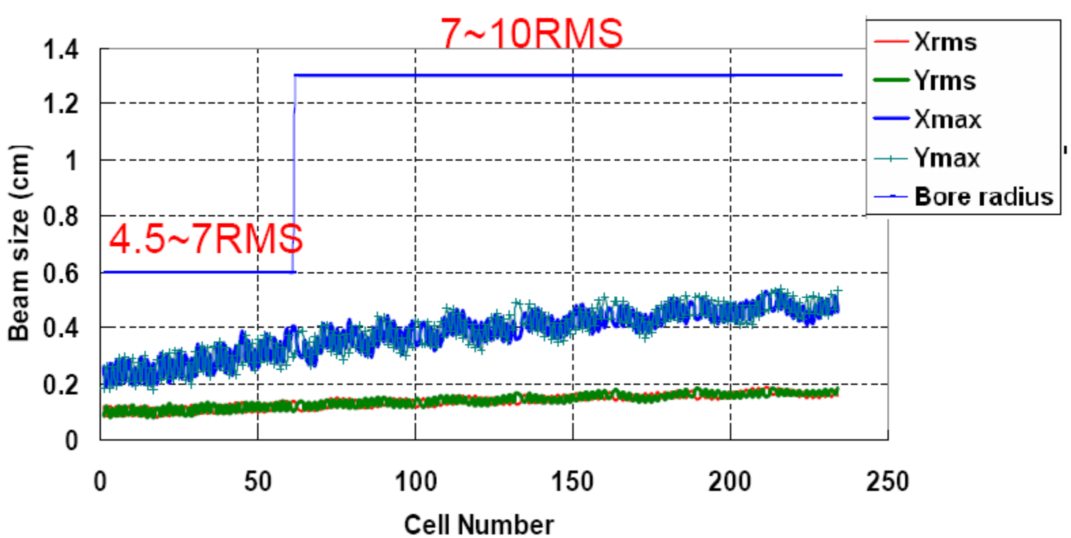




Beam Losses and Collimations

Beam loss control in the linac

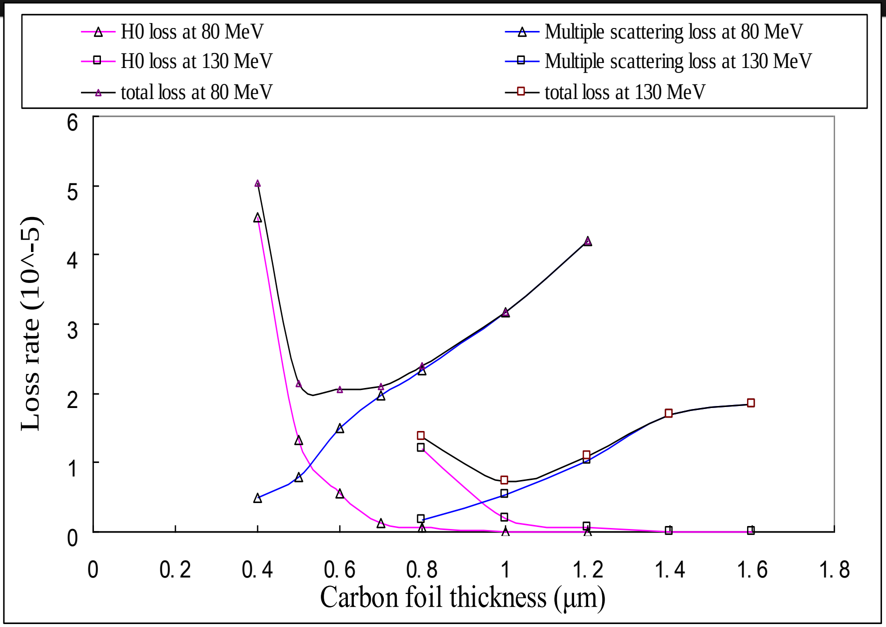
- **Chopped beam in LEBT**
  - Most stopped in the downstream slit
  - Some (emittance growth) will be lost inside the RFQ
- **Larger aperture in higher energy DTL tanks to reduce losses**

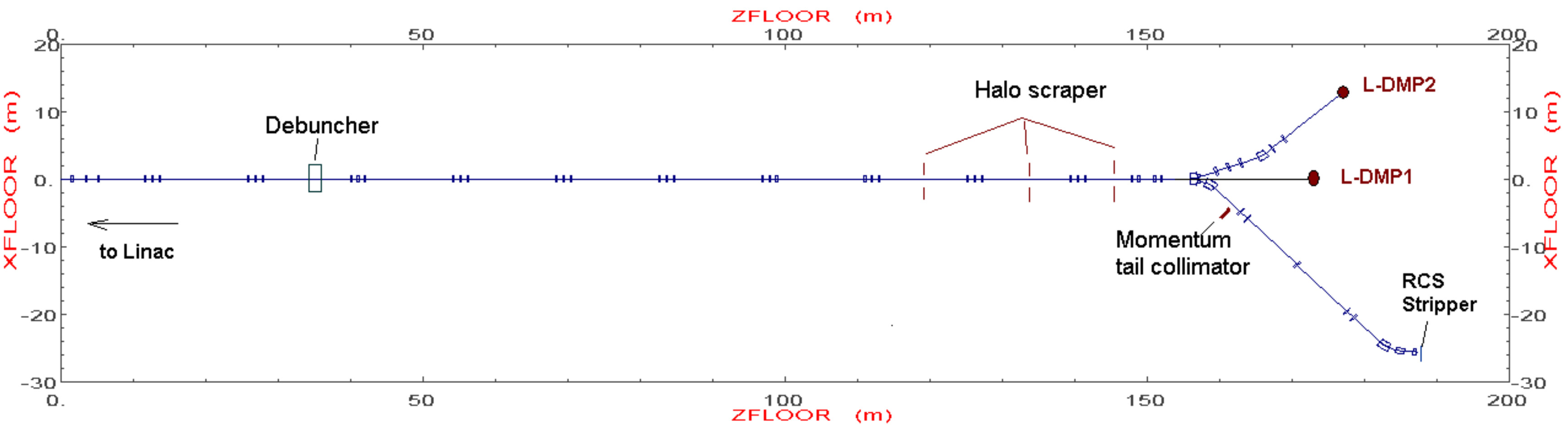


RMS and total beam size

Beam loss control in the LRBT

- Triplet cells to transport mixed H-/H+ beams (both matched)
- Optimized thickness for foil scrapers for trade-off between H0 and scattering H+ losses
- Momentum tail collimator to reduce uncontrolled loss in bending section.



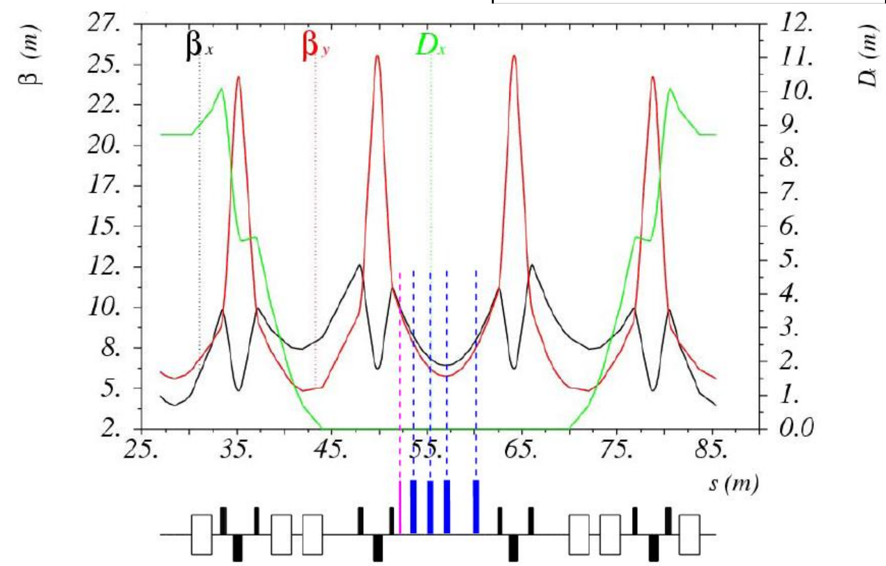


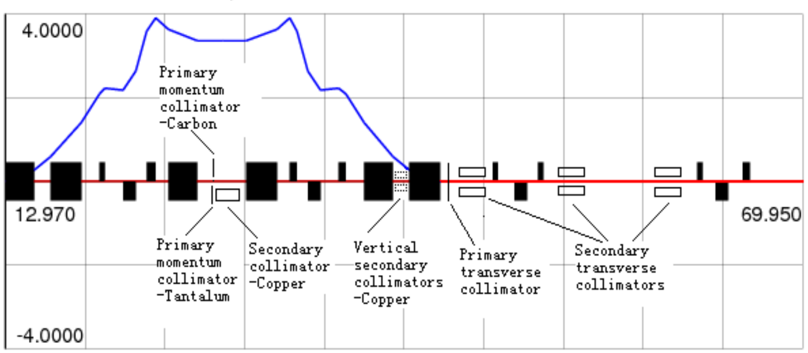
Beam loss and collimation in RCS

- **Beam loss mechanisms**
  - Nuclear scattering and multiple scattering
  - Non-stripped H- particles
  - RF capture loss
  - Transverse emittance growth due to space charge and non-linear resonance crossing
  - Loss at the extraction septum due to misfiring of the kickers
  - Accidental total beam loss
- **Collimation of lost particles**
  - Most happen at low energy or close to injection energy ➔ lower loss power and higher collimation efficiency
  - Total loss rate (<1kW): <5%at CSNS-I, <2% at CSNS-II, <1% at CSNS-III
  - Uncontrolled beam loss rate: <1W/m
- **Collimation method**
  - Two-stage collimation for both transverse and momentum halos

N. Wang's talk (TH02A04)

- **Transverse collimation**
  - In one of the dispersion-free long straight sections
  - One thin scatter and four absorbers (perhaps two needed for CSNS-I)
- **Momentum collimation**
  - Combined two-stage method
  - Primary: Carbon for δ>1.0%; Tantalum for δ<-1.0%
  - Secondary: transverse collimators; longitudinal (next turns)
  - Transverse beam correlation and collimation efficiency



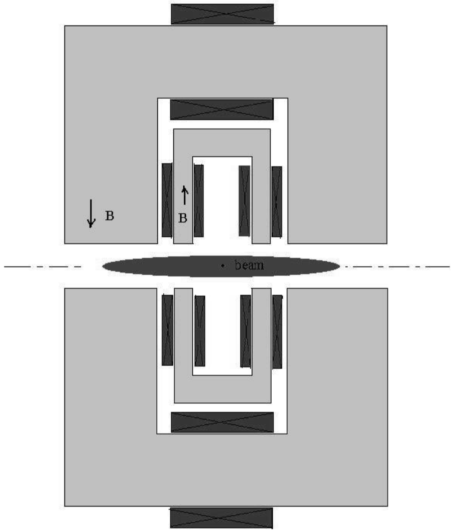


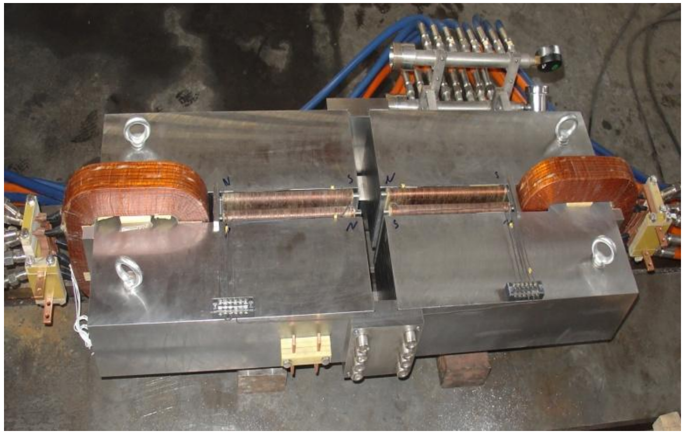
Poster: MOPD66

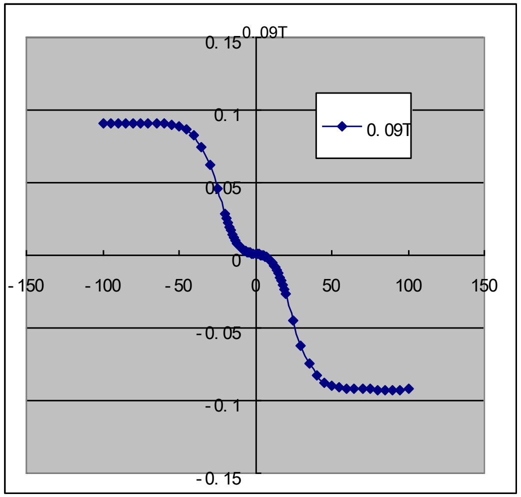
Beam Spot Uniformization at Target and Others

Beam spot uniformization at target

- In order to prolong lifetimes of target vessel and proton beam window, beam spots are made more or less uniform by using nonlinear magnets
  - Step-like field magnets (SFM) were proposed to transform irregular beam to quasi-uniform beam spot at the target [another option using octupoles is also under study]
  - Flat beams with different orientations in the last RTBT section are made to place SFMs, for the transformation in the horizontal and vertical planes decoupled







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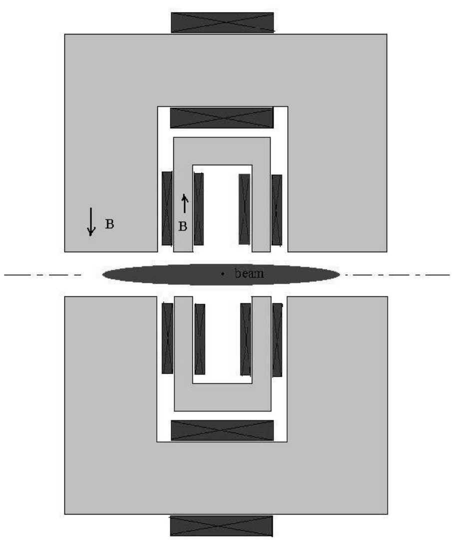
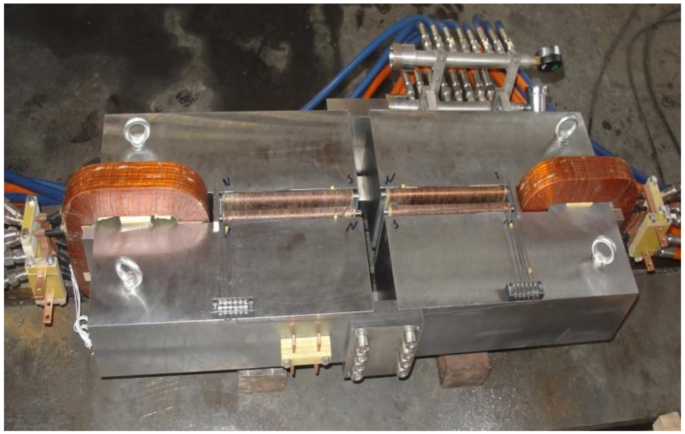
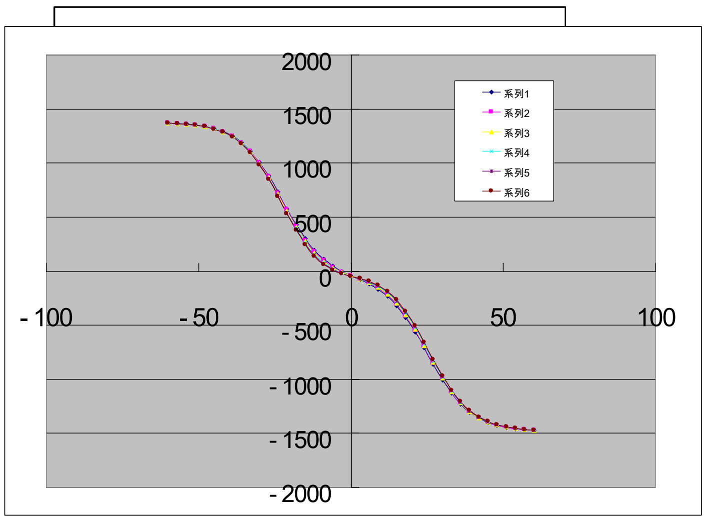
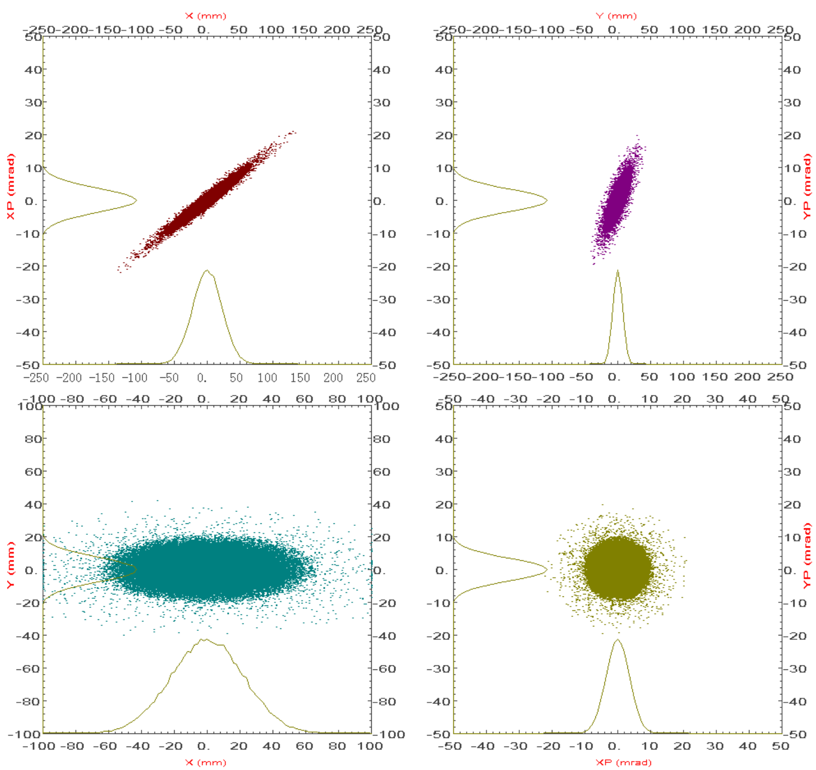


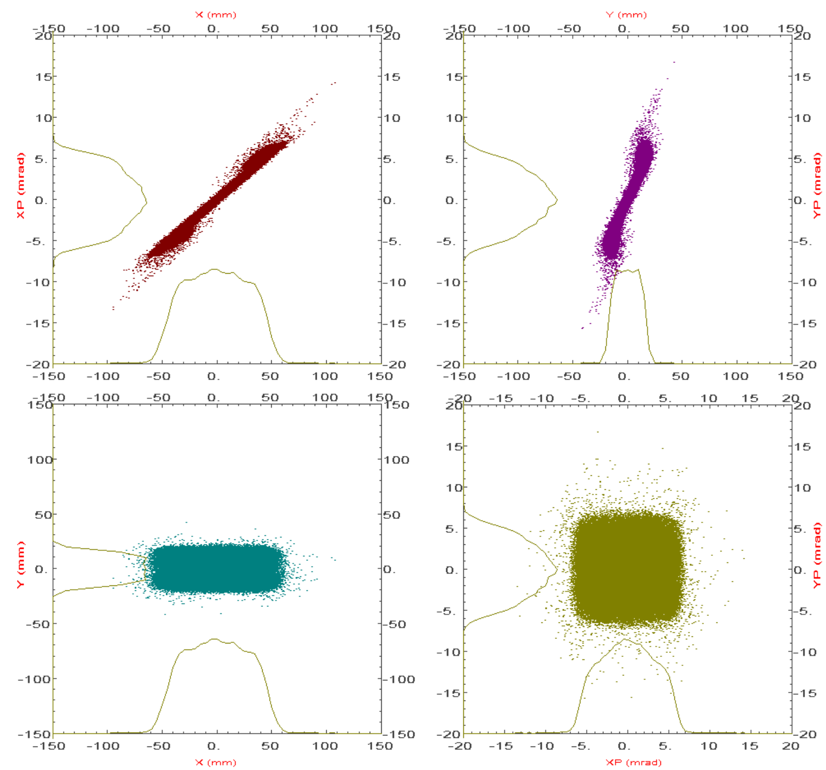




	w/o SFM	with SFM
Particles out of footprint	2.2%	2.0%
Particle out of target	0.64%	0.16%
Peak density (10^-2 A/m^2)	5.51	2.52



Without SFM



With SFM

Other high intensity aspects in CSNS

- **Beam loading effect**
  - Injection can be with non-chopped beam or chopped beam
  - With non-chopped injection, RF voltage starts from very low to obtain quasi-adiabatic RF capture. Beam loading effect is very important and more sophisticated LLRF with feed-forward is needed.
  - At CSNS upgrading, even with chopped beam injection, beam loading is also very important due to higher circulating current.
- **Lifetime of stripping foil**
  - Lifetime of the main stripping foil becomes a serious concern at CSNS-III. First temperature estimate shows similar to the SNS/AR one at 1.4 MW.
  - CSNS uses relatively thicker and larger foil to reduce H-/H0 particles

Conclusions

- Following the experience of ISIS, SNS and J-PARC, the high intensity beam at CSNS is considered to be manageable
- Space charge effects play important roles in both the linac and the RCS, even in the beam transport line LRBT. They are key in limiting the accumulated particles.
- Uncontrolled beam loss rate is taken to be 1W/m, sophisticated collimations are taken to localize most of lost particles in the whole CSNS accelerator.
- Major factors in limiting the power increase in the CSNS upgrading have been considered.

Thanks for your attention!