Institute of High Energy Physics

Instability investigation of China-ADS Injector-I SC section design

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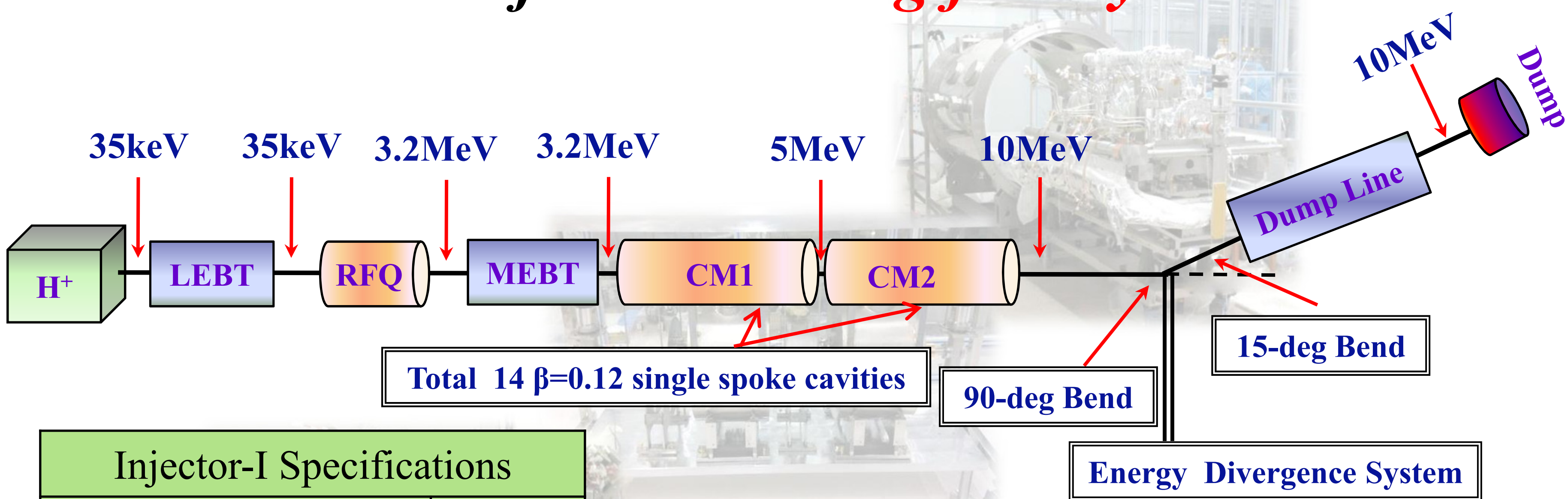
Lund, Sweden, July 3rd ~9th , 2016

Outline

1. Introduction
2. SC section design consideration
3. Lattice design
4. Beam dynamics
5. Experiment results
6. Summary

The layout and specifications of ADS Injector-I testing facility



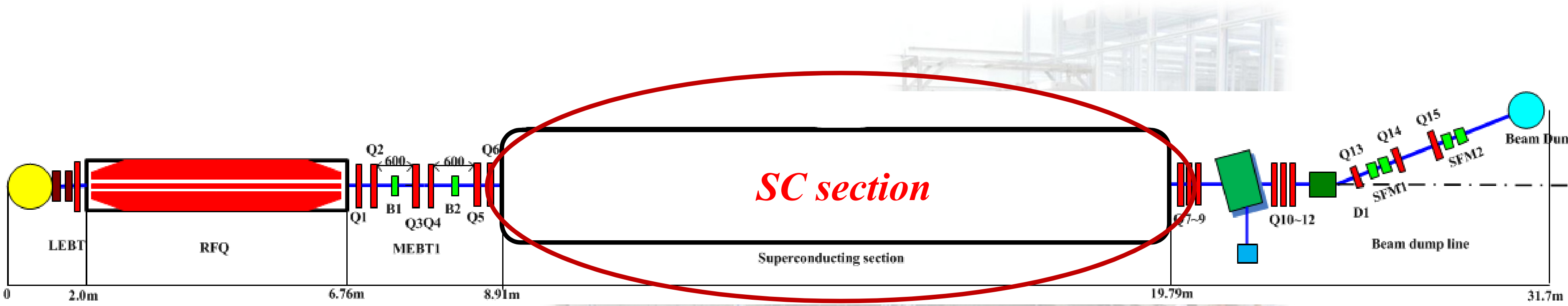
Injector-I Specifications	
Particle	H^+
Output Energy (MeV)	**10**
Current (mA)	**10**
Beam power (kW)	100
Duty factor (%)	**100**
RF frequency (MHz)	**325**

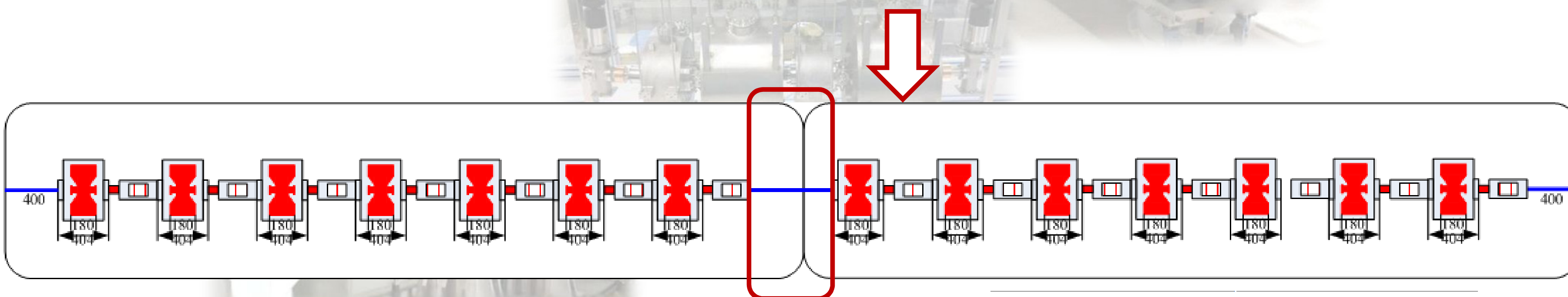
Injector-I consists of:

- ECR source providing with 35keV proton
- LEBT: including a chopping system
- 4-vane type copper structure RFQ: 3.2MeV
- MEBT
- SC section: including two cryomodules → **5**/10MeV
- Energy divergence system & beam dump line

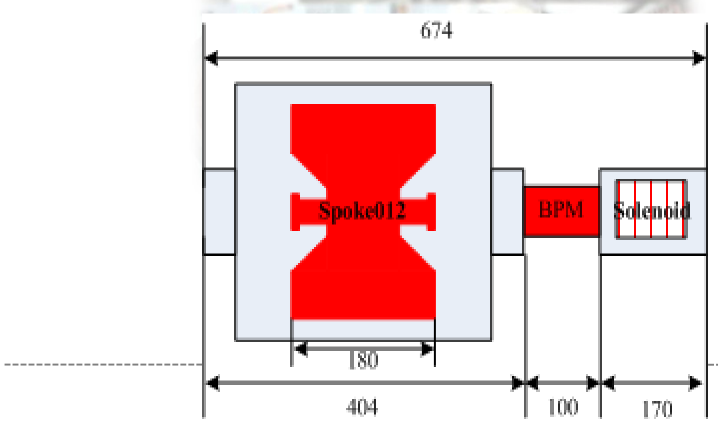
1. Introduction

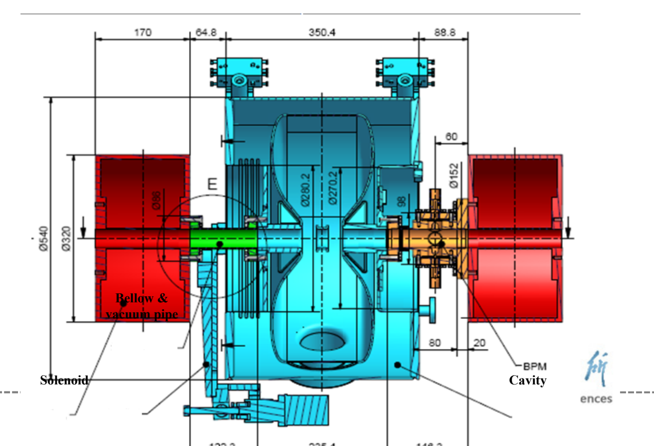
SC section of the ADS Injector-I





570 mm





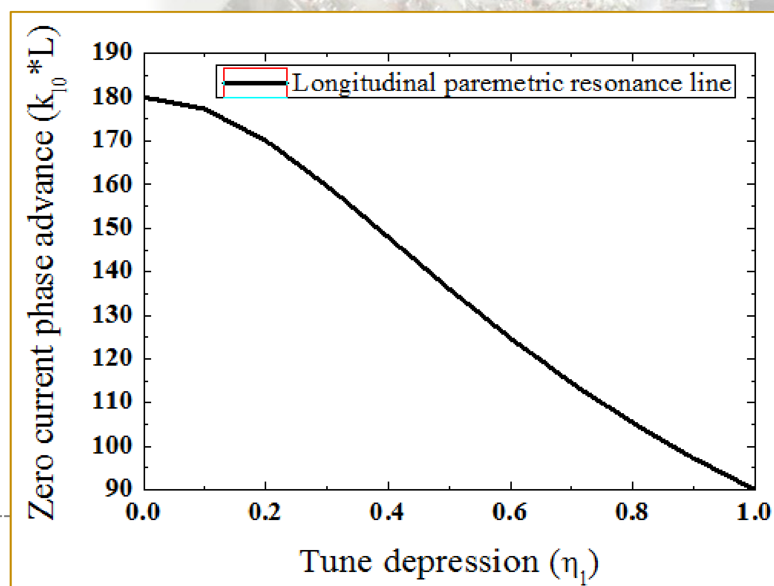
Longitudinal instability

Mismatch parametric resonance

$$k_{mm} L = \pi$$

⇩

$$k_{\ell 0} = k_{mm} \Big/ \sqrt{1+3\eta_l^{\,2}} = \pi / L \Big/ \sqrt{1+3\eta_l^{\,2}}$$

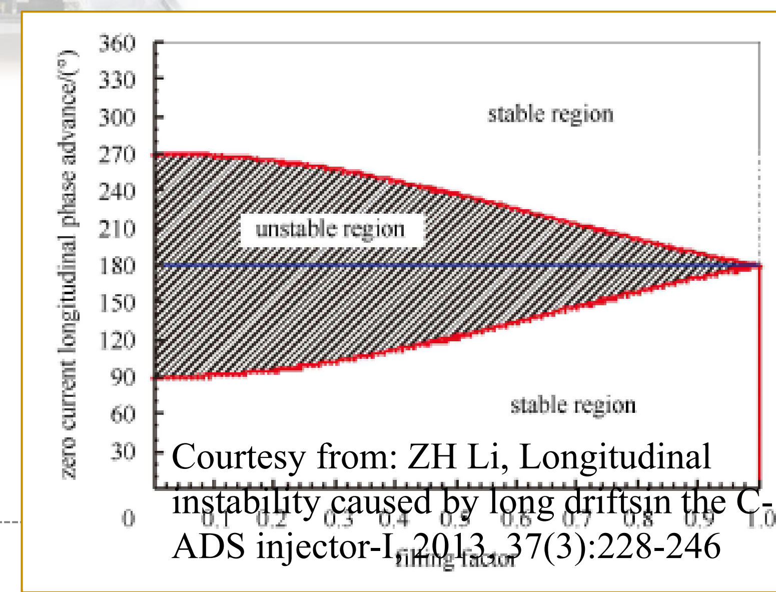


When filling factor is considered

$$\varepsilon = \frac{\sigma_{l0}}{2} \frac{\sin(\pi l_{eff} / L)}{\pi l_{eff} / L}$$

L : Periodical length

L_{eff} : Longitudinal effective length



Courtesy from: ZH Li, Longitudinal instability caused by long driftsin the C-ADS injector-I, 2013, 37(3):228-246

2. SC section design consideration

Longitudinal instability

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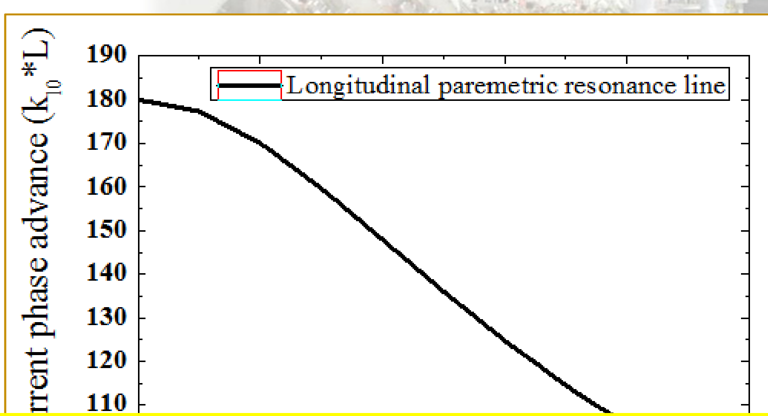

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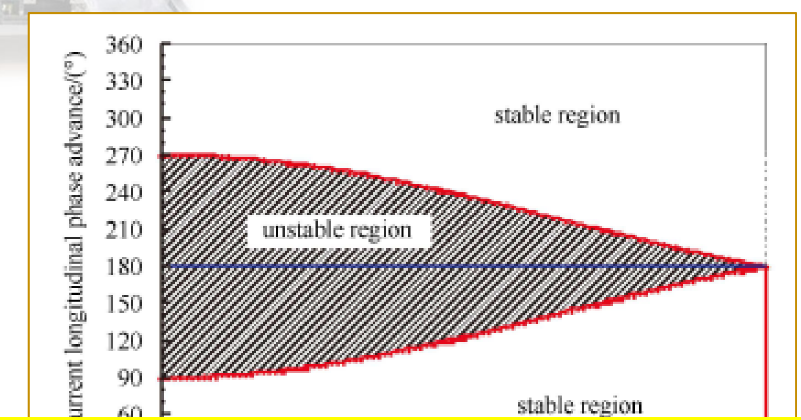

However all these effect could be avoided by keeping the zero current longitudinal phase advance smaller than 90 degree!!!

Transverse instability

Resonant conditions:

- Envelope instability
- Fourth order resonance
- Third order resonance
- Sixth order resonance

……………

Defined by: $nk = m\times 360$

n : *nth order of resonance*

m : *harmonic of the focusing lattice*

However only the 90° stop band and 60° degree stop band had been manifested as described in these two papers.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 7, 024801 (2004)

Stability properties of the transverse envelope equations describing intense ion beam transport

Steven M. Lund*
Lawrence Livermore National Laboratory, University of California, Livermore, California 94550, USA

Boris Bukh
Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720, USA
(Received 13 June 2003; published 11 February 2004)

PRL 115, 204802 (2015) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2015

Space-Charge Structural Instabilities and Resonances in High-Intensity Beams

Ingo Hofmann[1,2,*] and Oliver Boine-Frankenheim[1,2]
[1]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany*
[2]*Technische Universität Darmstadt, Schlossgartenstrasse 8, 64289 Darmstadt, Germany*
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PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 12, 054204 (2009)

Fourth order resonance of a high intensity linear accelerator

D. Jeon,[1,*] L. Groening,[2] and G. Franchetti[2]
[1]*SNS, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
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Sixth-Order Resonance of High-Intensity Linear Accelerators

Dong-O Jeon,[1,*] Kyung Ryun Hwang,[2] Ji-Ho Jang,[1] Hyunchang Jin,[1] and Hyojae Jang[1]
[1]*Institute for Basic Science, Daejeon, Republic of Korea*
[2]*Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*
(Received 6 February 2015; published 6 May 2015)

2. SC section design consideration

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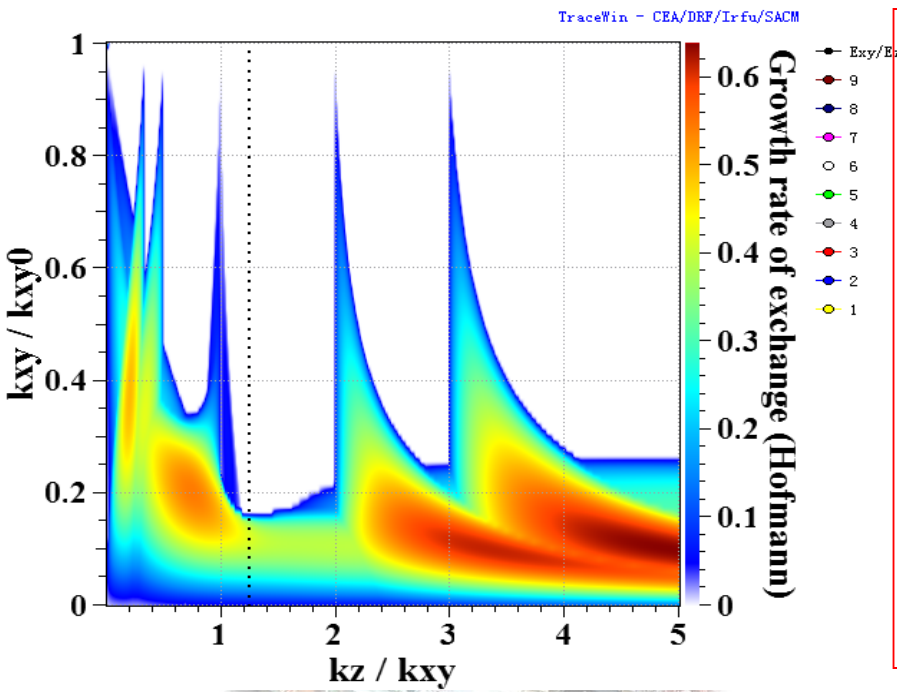
And the 90° and 60° stop band could be avoided by keeping the zero current transverse phase advance no bigger than 60 degree!

2. SC section design consideration

Transverse and longitudinal coupling



- One important beam dynamics resonant condition coupling the longitudinal and transverse motion is the $k_l = 2k_t$ resonance.
- Analysis of the coupling effect showed substantial amplitude and emittance growth*.

- Further analyses show also other anisotropy instabilities identified by k_z / k_t = 1/3, 1/2, 1 and 2 which lead to emittance transfer between transverse and longitudinal degrees of freedoms as described in the paper.

The linac was designed with fixed zero current phase advance ratio to give a current free design.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 6, 024202 (2003)

Space charge resonances in two and three dimensional anisotropic beams

I. Hofmann,* G. Franchetti, and O. Boine-Frankenheim
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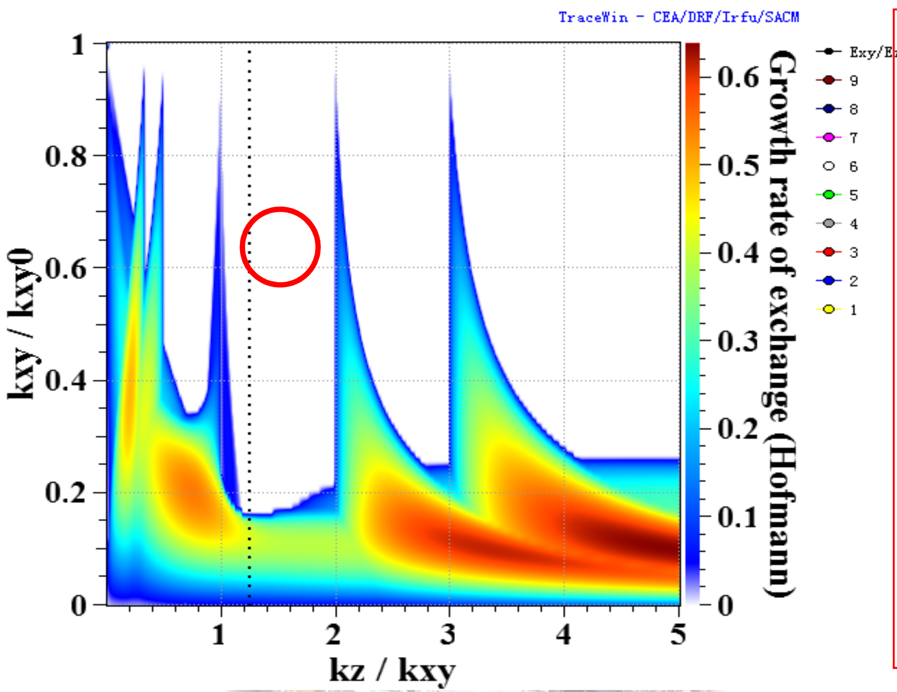

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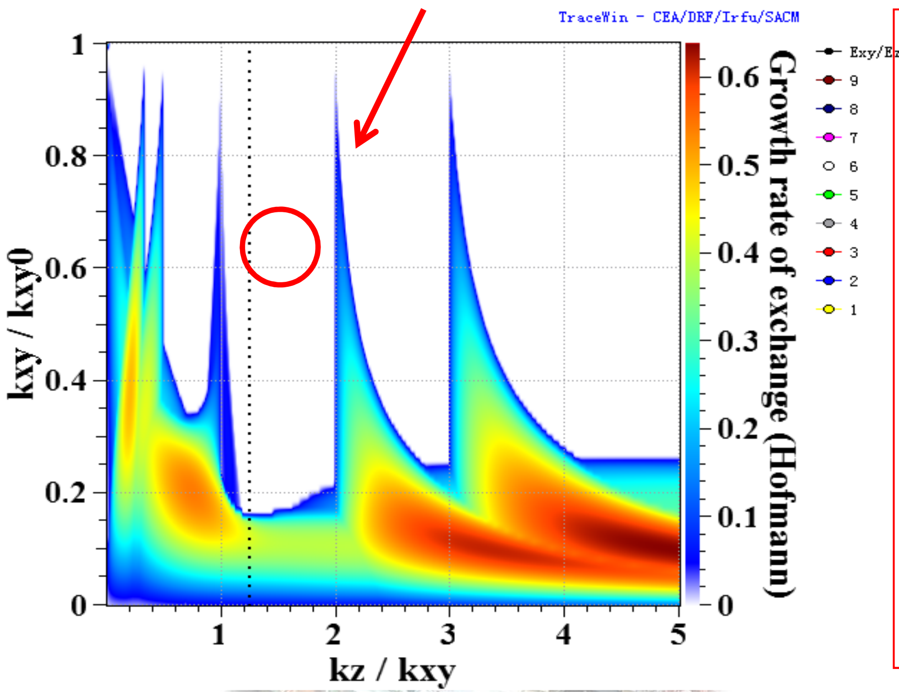

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Simulation conditions

- Multi-particle tracing with TraceWin program was used to investigate the beam performances while the working points were sitting on the resonance peaks
- Zero current phase advance ratio of

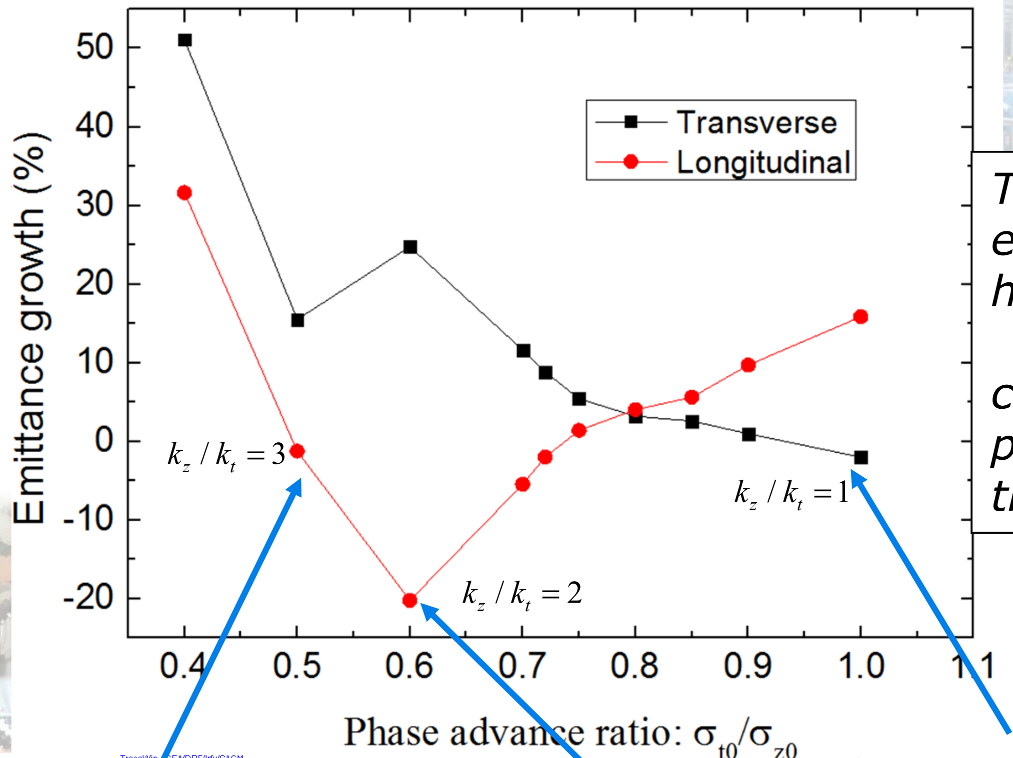
  σ_{t0} / σ_{l0}=0.4/0.5/0.6/0.7/0.72/0.75 cases were studied
- Models instead of 3d fields were used in the simulation to avoid introducing nonlinear effect
- Input energy: 3.2MeV / Peak current: I=10mA/14 periodical cells
- 4σ/5σ truncated Gaussian distribution were assumed for the initial transverse and longitudinal beam
- Norm. RMS emittance of the initial beam are:

  ε_x / ε_y / ε_z=0.198/0.199/0.159 mm.mrad
- 99072 particles

3. Lattice design

Emittance growths @ different working points

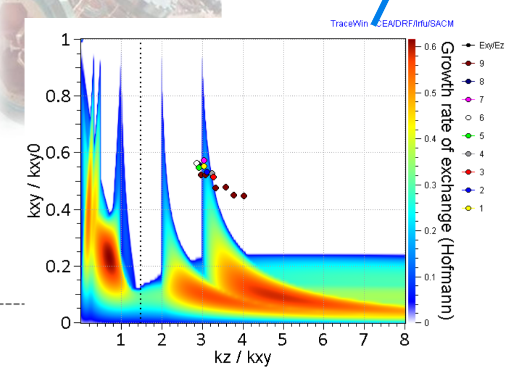
Emittance exchanges were observed for the working points which encountered with the resonance peaks.

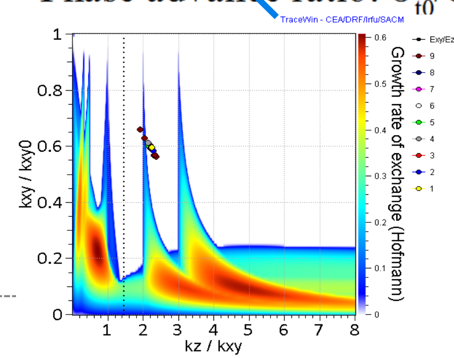


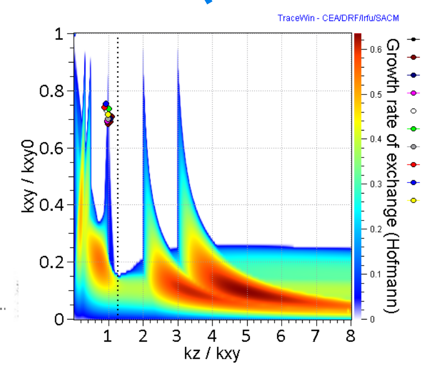
The most severe emittance transfer happened for the

$k_z / k_t = 2$

case which is well predicted by the theory!!







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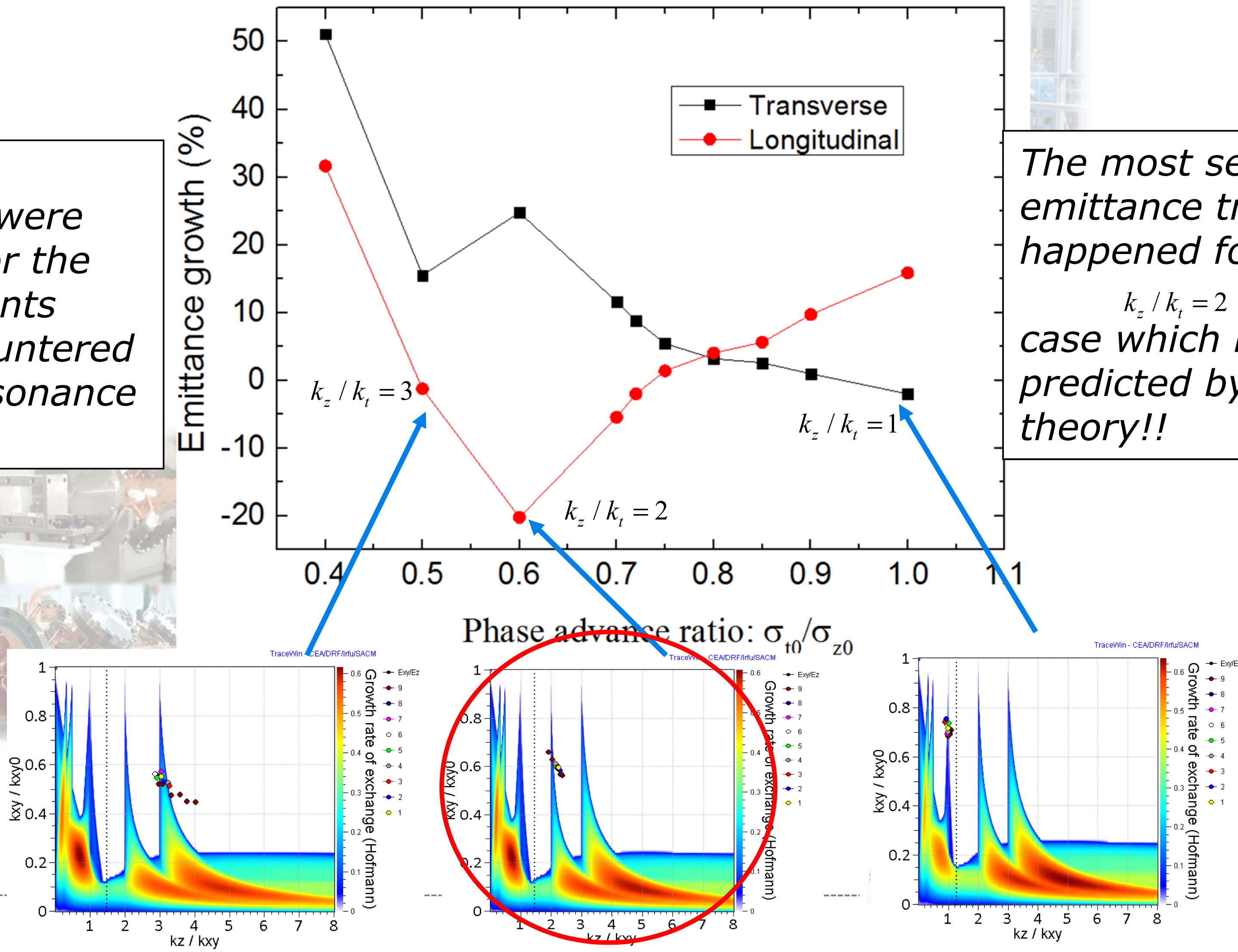

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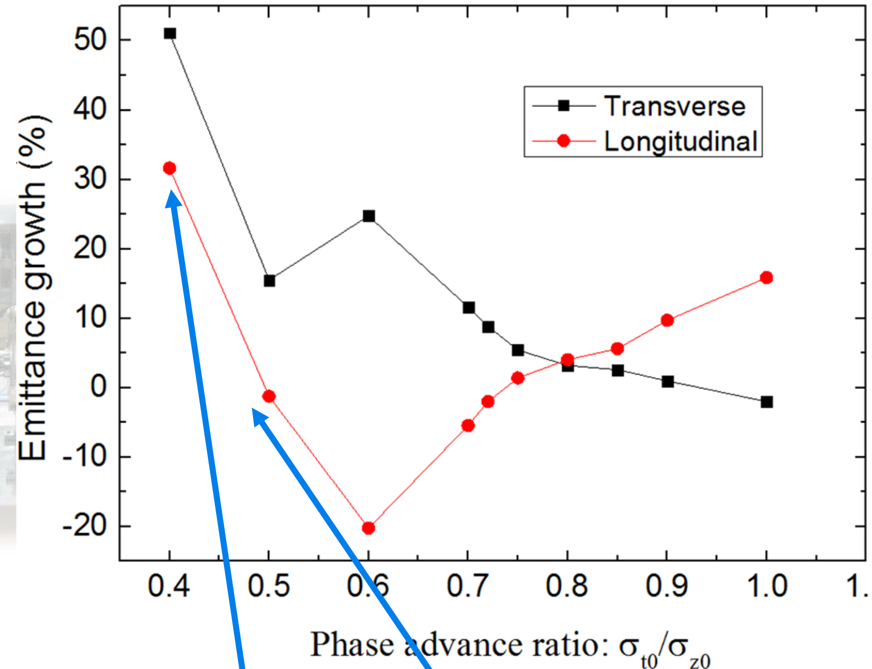
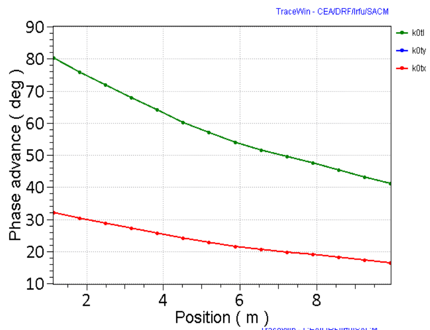
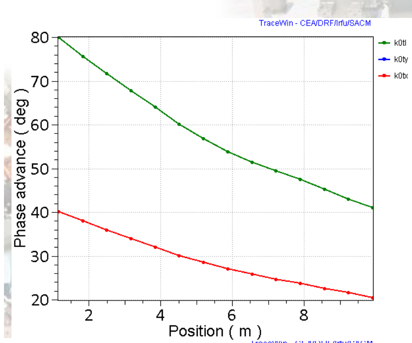
3. Lattice design

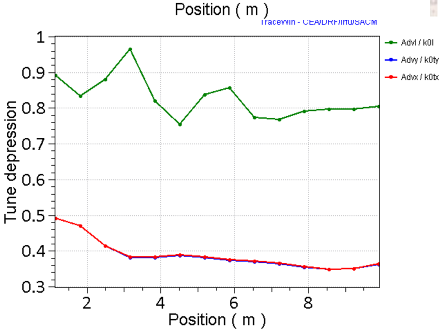
Emittance growths @ different working points

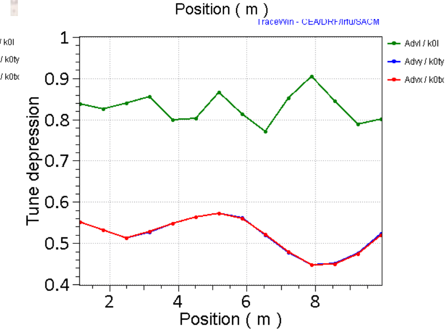
- Beam losses occurred for these two cases as shown in the right figure: $\sigma_0 < 40^\circ$
- While the tune depression were around 0.4~0.5 in these two cases.

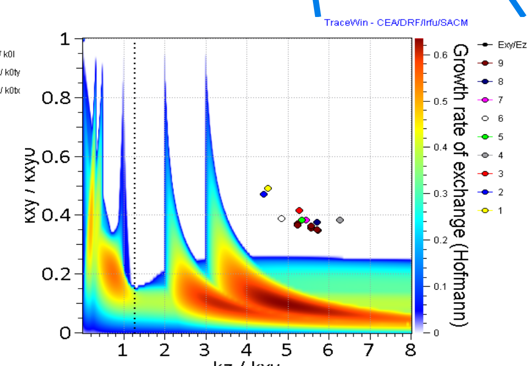


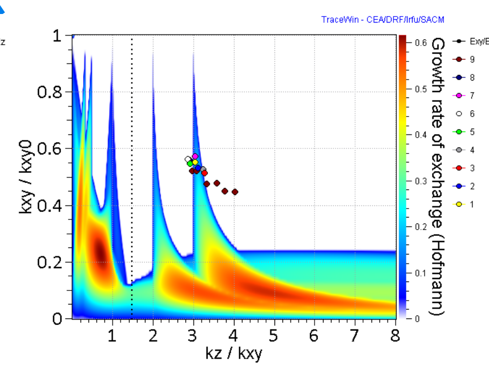






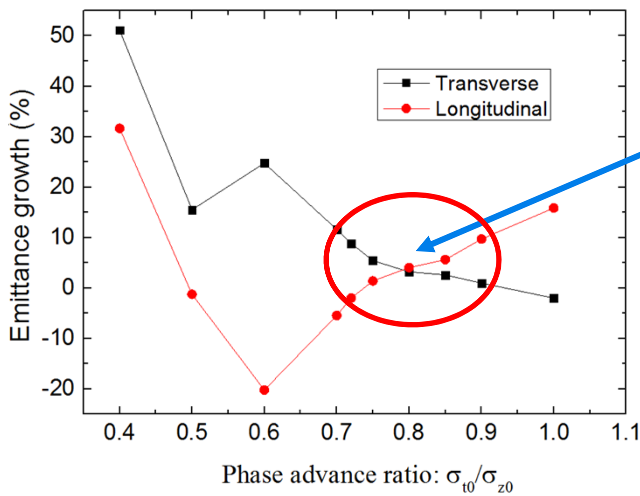


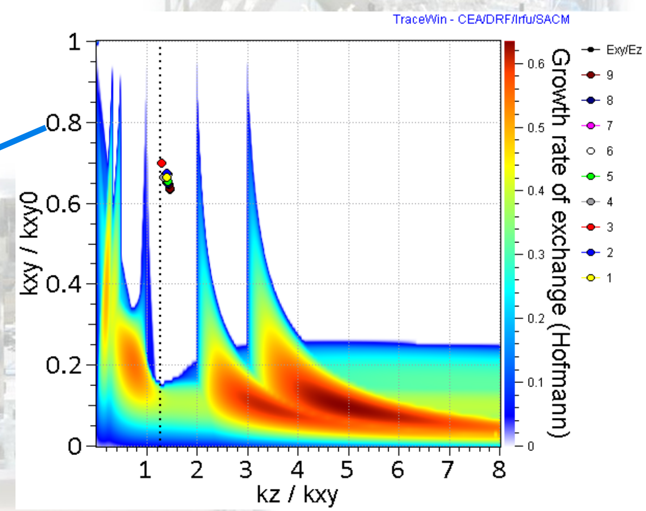




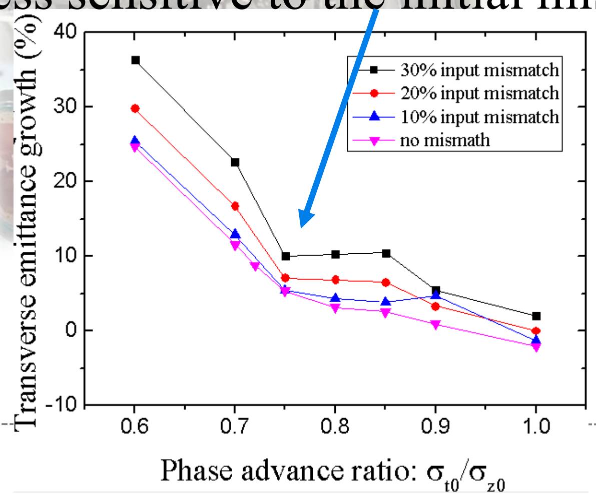
Footprint area selection

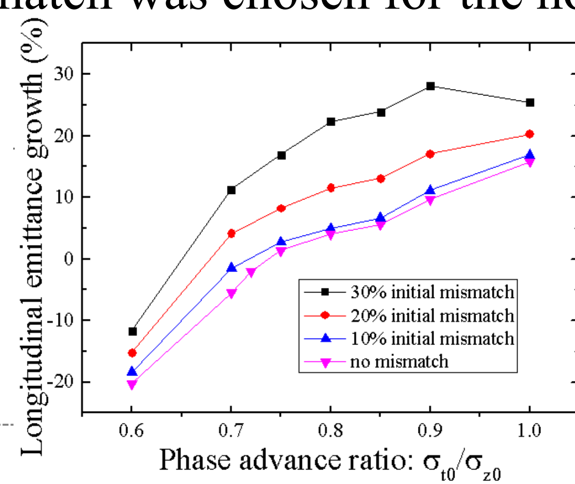
The working points were chosen between the $k_z / k_t = 1$ and $k_z / k_t = 2$ stop bands.



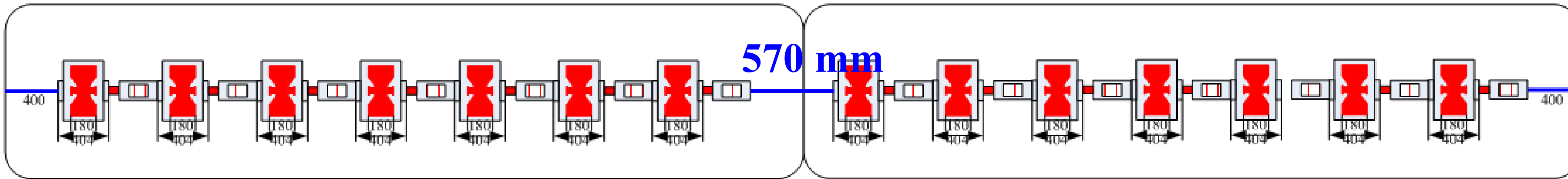


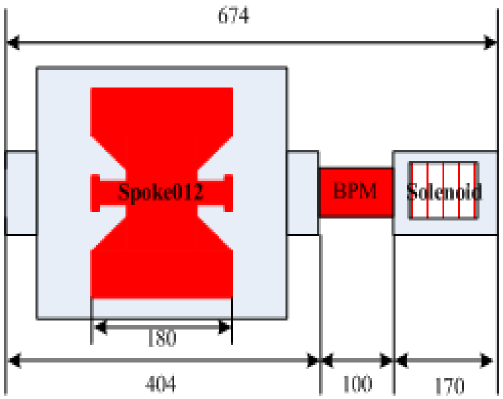
The one less sensitive to the initial mismatch was chosen for the nominal design.





3. Lattice design

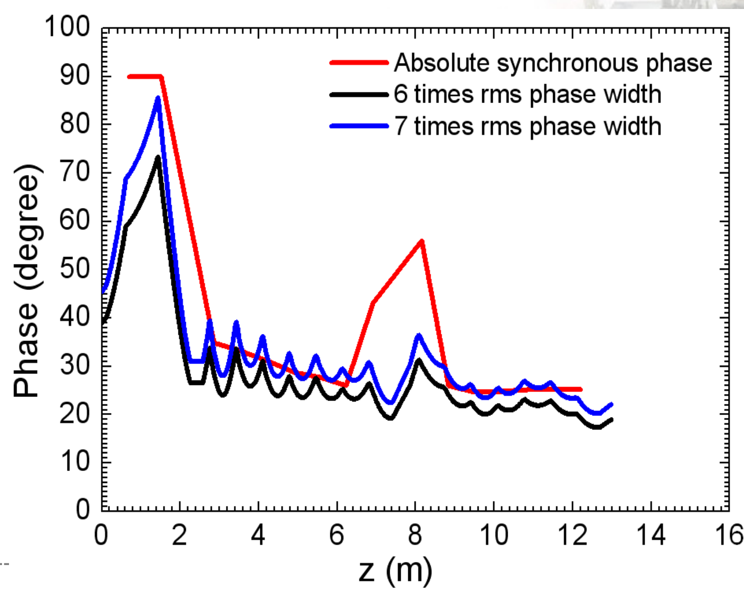




One period

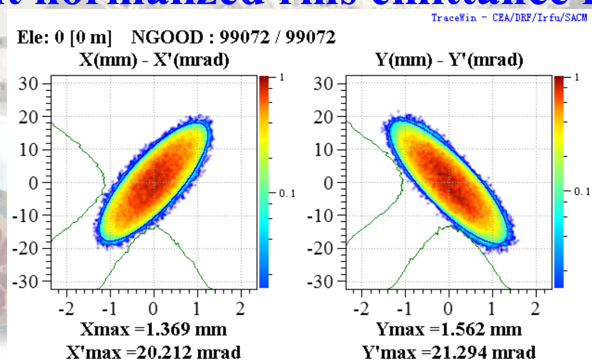
- 1 β=0.12 spoke cavity
- 1 SC solenoid
- 1 cold BPM

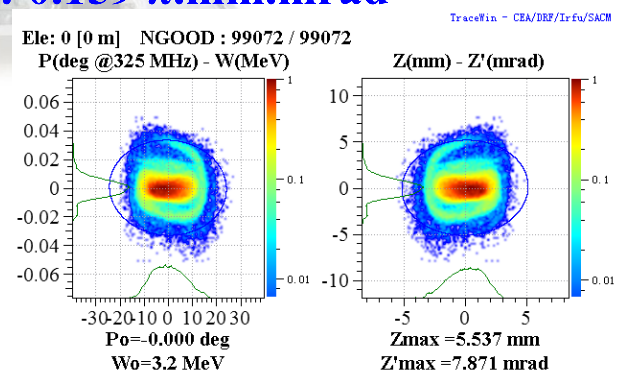
Cav Number	Eacc (MV/m)	Sol (A)
1	4.97	170.4
2	4.97	170.4
3	5.09	170.4
4	5.28	170.4
5	5.42	170.4
6	4.36	132.3
7	4.69	184.2
8	4.14	186.5
9	3.94	132.3
10	6.61	170.4
11	6.83	170.4
12	6.96	168.8
13	7.07	167.0
14	7.19	164.7



Beam dynamics conditions

- **The SC section simulation was integrated with the MEBT section;**
- **TraceWin program was used for beam dynamics and error analysis; using RFQ simulated output:**
  - **Simulated with Parmteq.**
  - **4d waterbag input with 100000 macro particles for the RFQ entrance.**
  - **Output Normalized rms emittance in x and y:**
    0.198 π.mm.mrad /0.199 π.mm.mrad.
  - **Output normalized rms emittance in z: 0.159 π.mm.mrad**



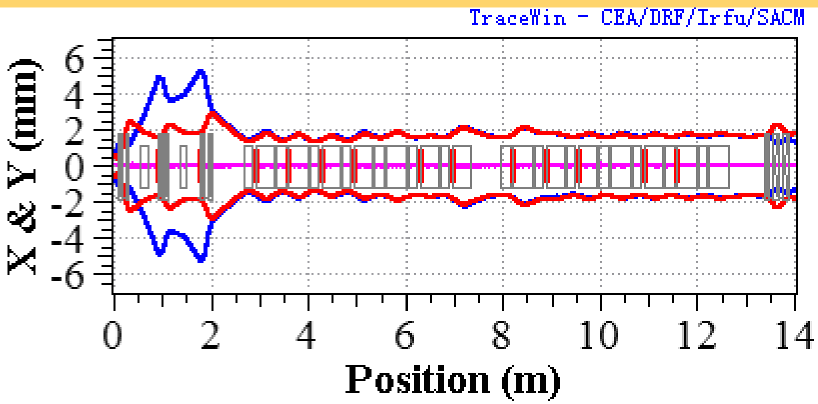


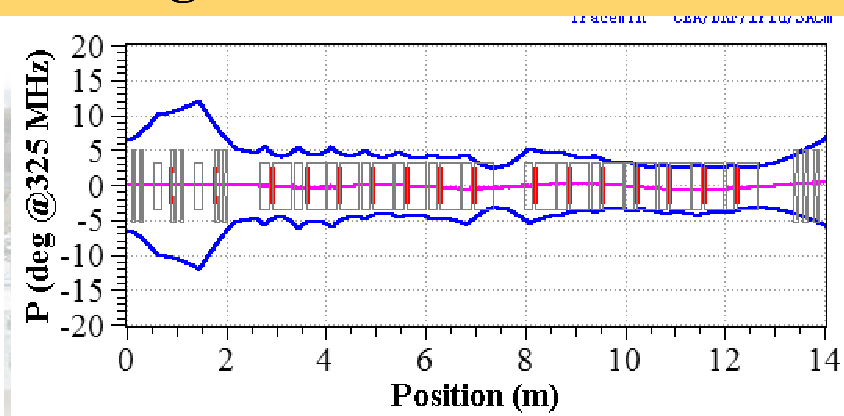
- **3d cavity and solenoid fields were used in the multi-particle simulations.**

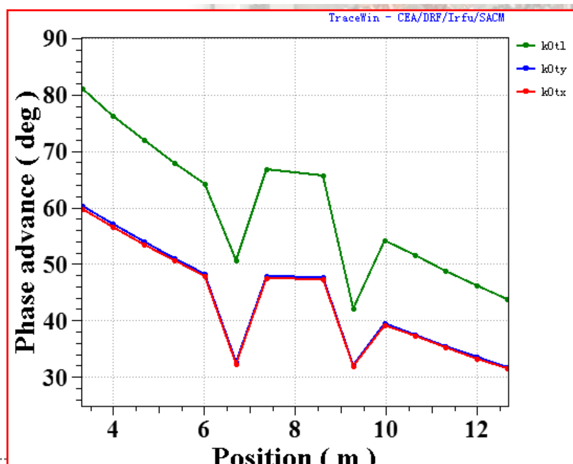
4. Beam dynamics

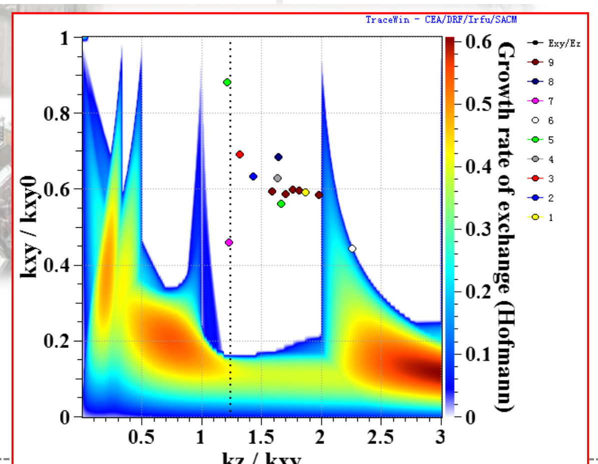
Beam dynamics results for nominal design

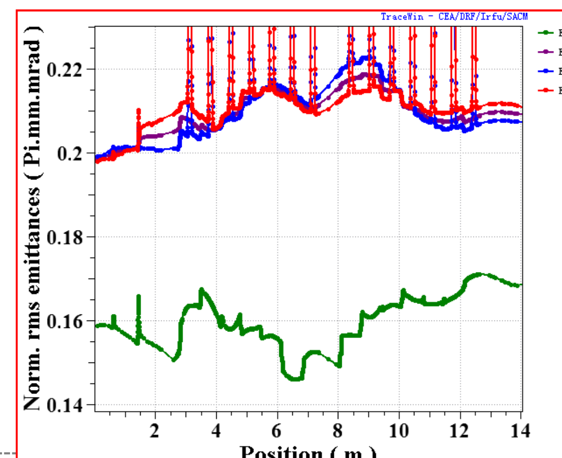
Simulation showed smooth rms envelope evolution with few percent of RMS normalized emittance growths.



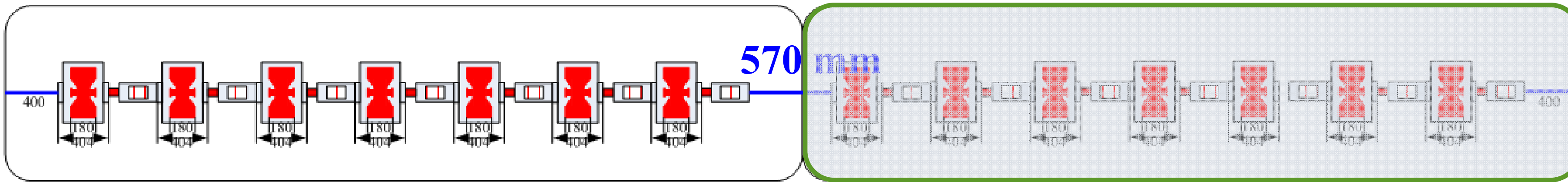


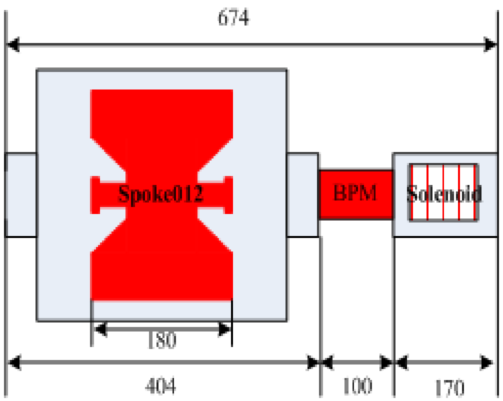






5. Experiment results





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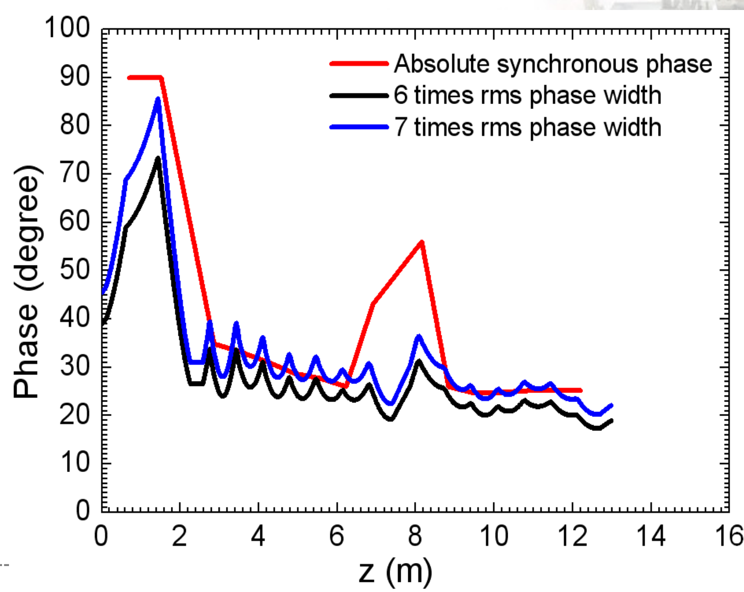

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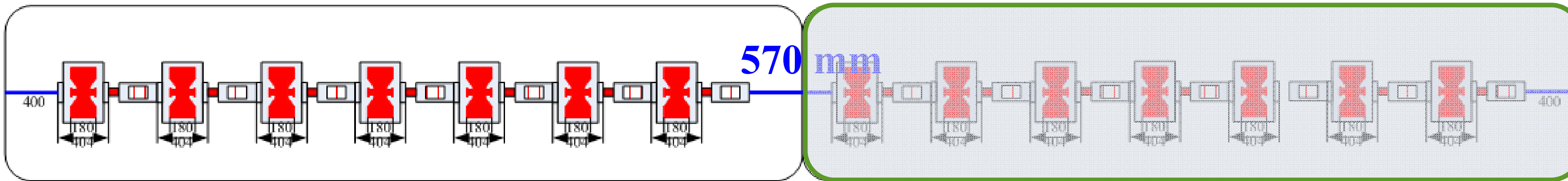
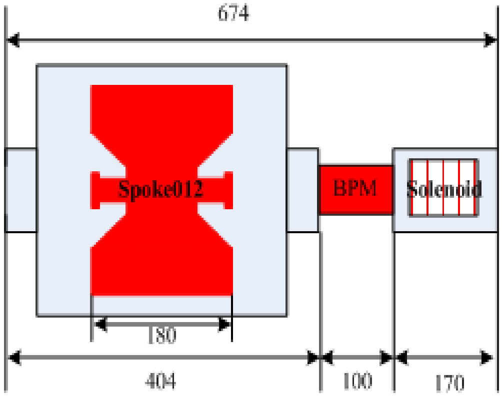
13	7.07	167.0
14	7.19	164.7

5. Experiment results

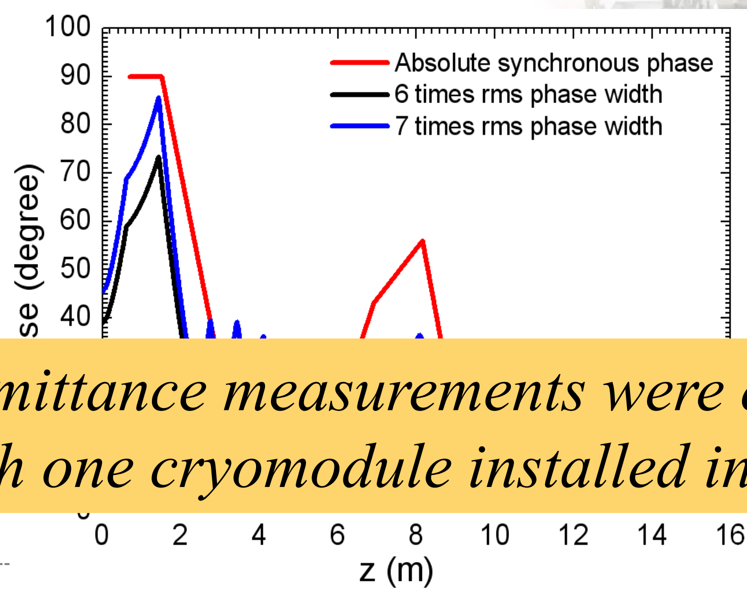




One period

- 1 β=0.12 spoke cavity
- 1 SC solenoid
- 1 cold BPM

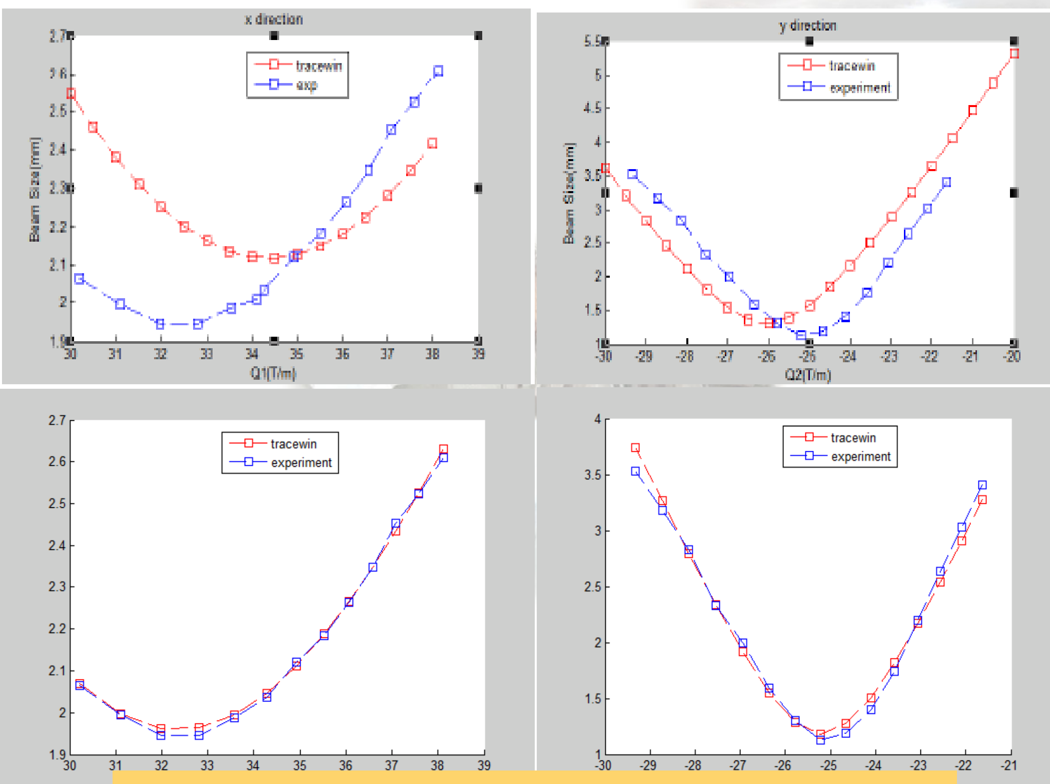
Cav Number	Eacc (MV/m)	Sol (A)
1	4.97	170.4
2	4.97	170.4
3	5.09	170.4
4	5.28	170.4
5	5.42	170.4
6	4.36	132.3
7	4.69	184.2
8	4.14	186.5
9	3.94	132.3
10	6.61	170.4
14	7.19	164.7



Emittance measurements were carried out for the 5MeV test stand with one cryomodule installed in the tunnel as shown in the top figure.

5. Experiment results

Input twiss parameters &emittance of the SC section



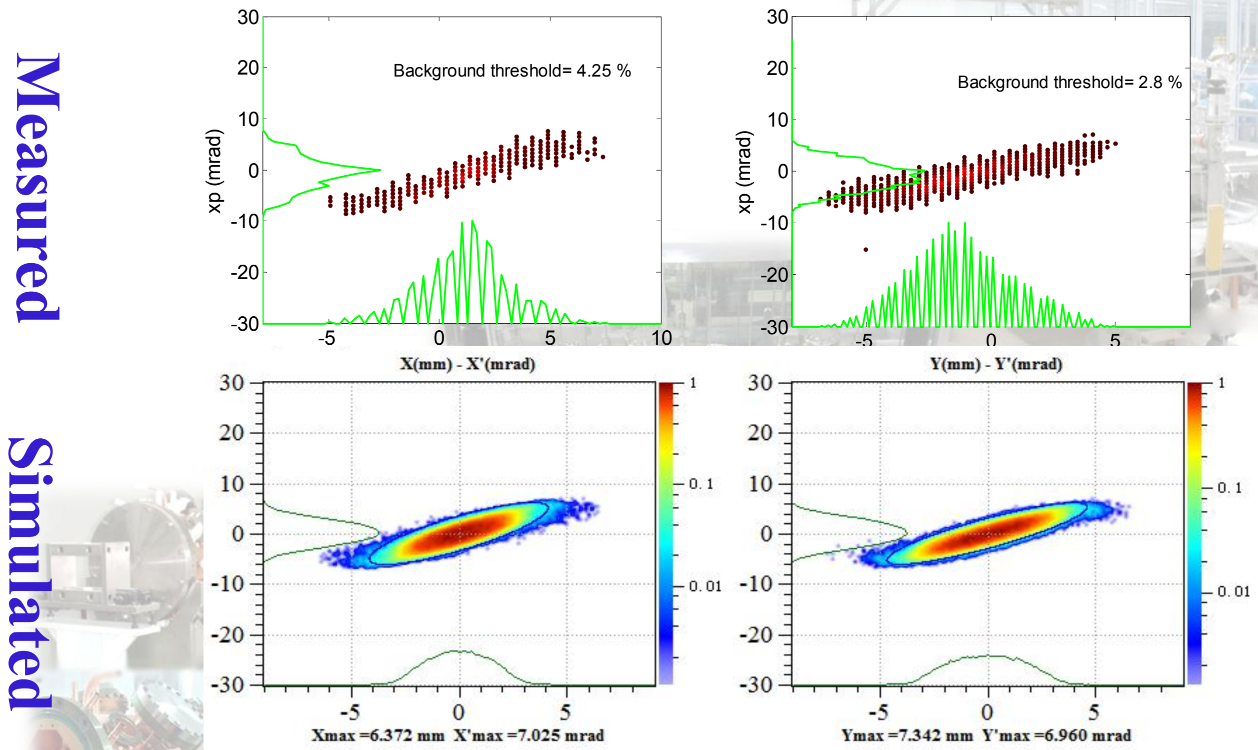
- Quad scan method was used at the MEBT section for RFQ exit emittance measurement
- Evolutionary algorithm instead of transfer map was used to consider the space charge effect
- Measurements beam RMS size with different Quads setting consistent with TraceWin simulation results as shown in the below figures (space charge effect was considered)
- Upper figures showed the deviation while SC effect was not considered in the data processing of the transfer map.

Slide provide by Y. L. zhao, IHEP CAS

Institute of High Energy Physics Chinese Academy of Sciences

6. Experiment results

Transverse emittance measurement results V.S simulation at the exit of CM1 with nominal design

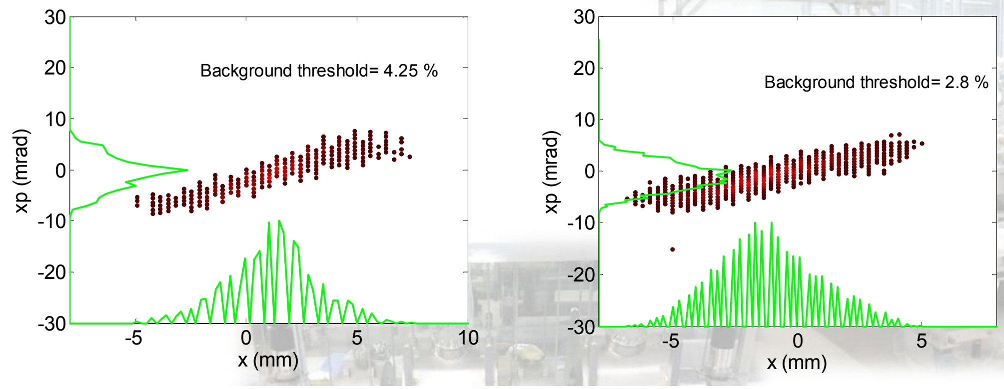


Parameters		αx/αy	βx/ βy (mm/mrad)	$E_{n,rms,x/y}$ (π mm.mrad)
CM1 exit	Simulation results (errors not included)	-1.53/-1.55	1.20/1.63	0.20/0.25
	Measurement (Double slits)	-2.12/-1.97	1.56/1.81	0.29/0.27
RFQ exit	Simulation results (4D WB input)	-1.31/1.46	0.12/0.13	0.20/0.20
	Measurement (Quads scan: with SC)	-1.22/1.10	0.16/0.10	0.16/0.24

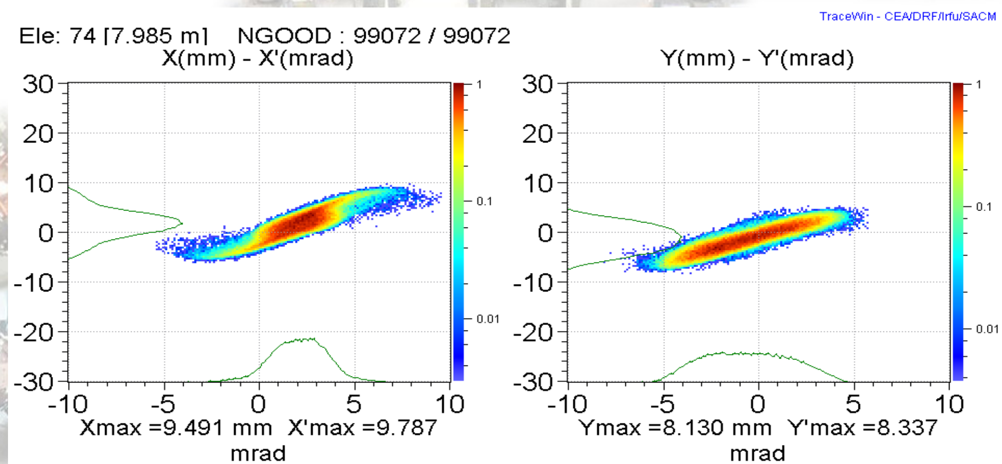
3. Experiment results

Transverse emittance measurement results V.S simulation at the exit of CM1 ***with nominal design***

Measured



Simulated with errors

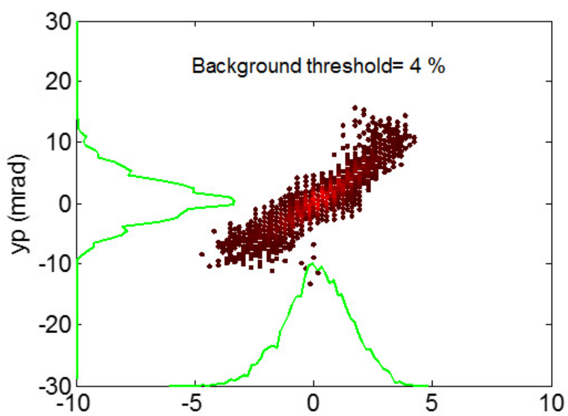


Parameters		αx/αy	βx/ βy (mm/mrad)	$E_{n,rms,x/y}$ (π mm.mrad)
CM1 exit	Simulation results (with errors)	-1.68/-2.12	1.28/2.07	0.28/0.28
	Measurement (Double slits)	-2.12/-1.97	1.56/1.81	0.29/0.27

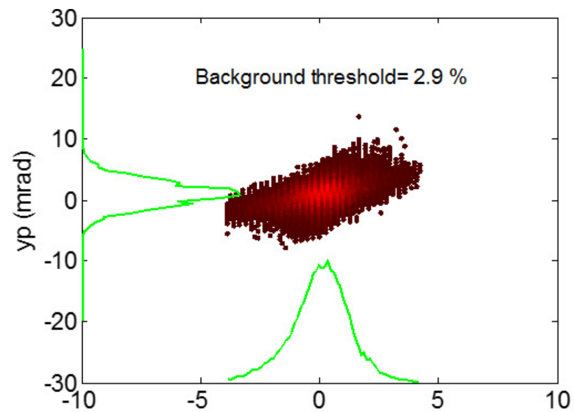
5. Experiment results

Emittance measurement results with different transverse over longitudinal zero current phase advance ratios

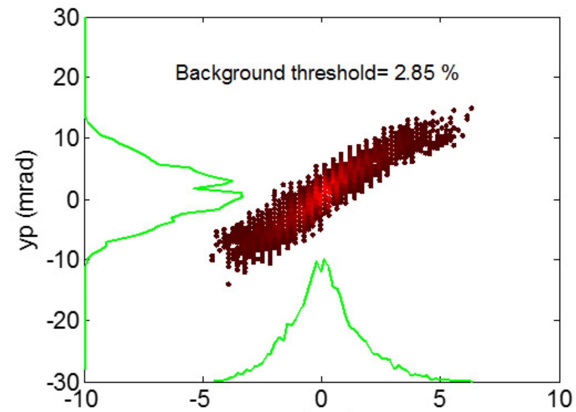
Phase advance ratio of 0.4



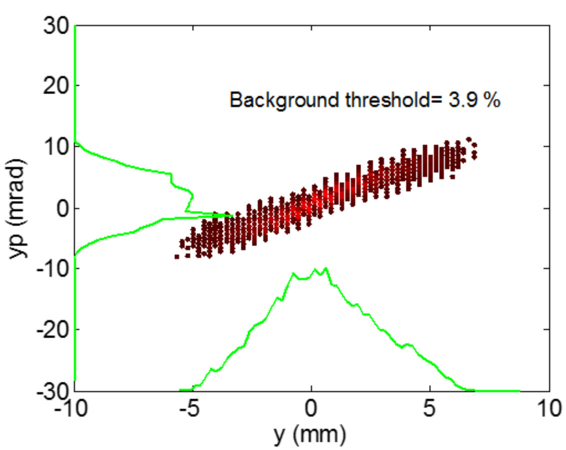
Phase advance ratio of 0.5



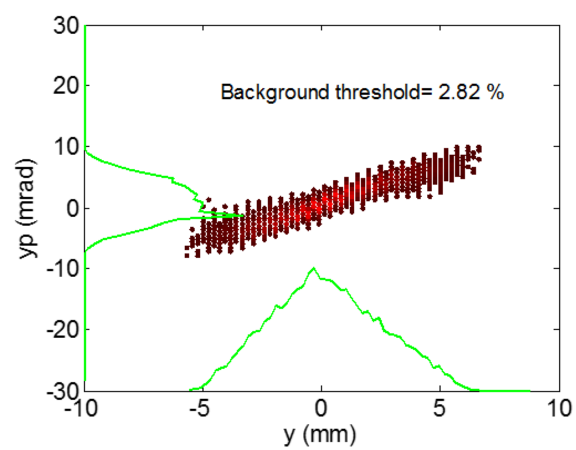
Phase advance ratio of 0.6



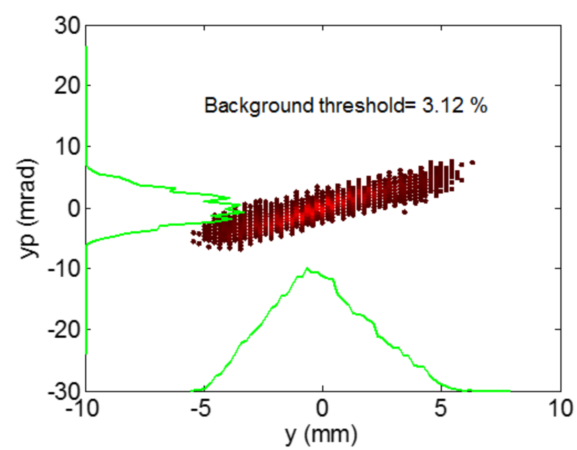
Phase advance ratio of 0.7



Phase advance ratio of 0.72



Phase advance ratio of 0.75

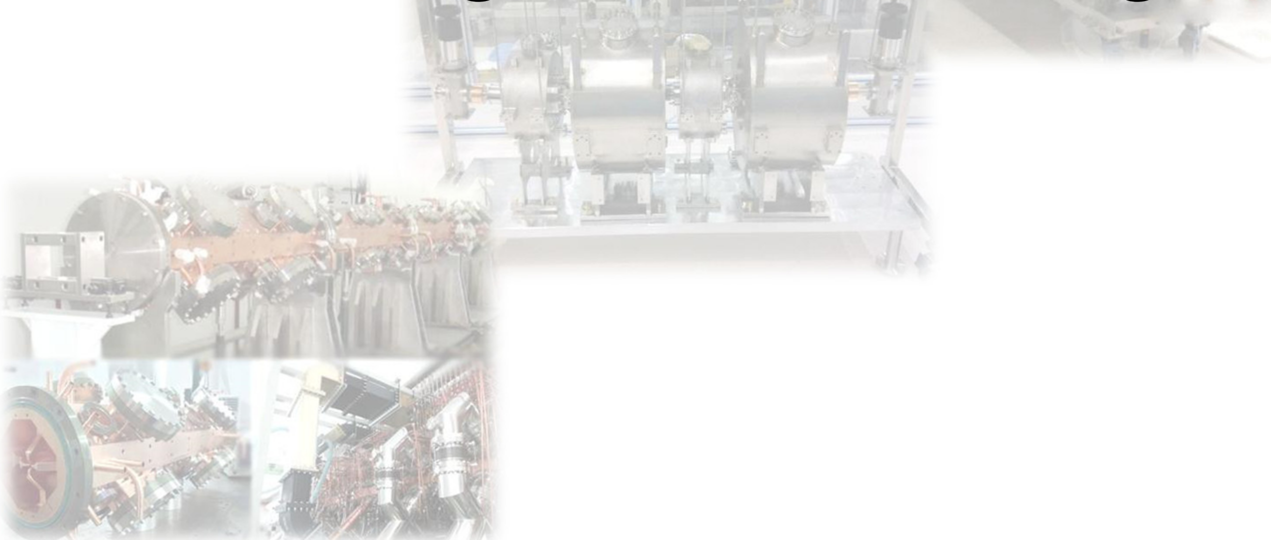


6. Summary

- Different instability factors were investigated during the design of the ADS injector-I SC section;
- Experiments were carried out for different zero current phase advance ratios of the 5MeV test stand SC section with 7 focusing periods;
- Beam was clearly twisted when the footprints were encountered with the resonance peaks, especially for the cases when zero current phase advances were smaller and the tune depression were around 0.4~0.5 ;
- More effects will be done to further understand the beam performances.

Acknowledgement

Sincere acknowledgement to the China ADS Injector-I commissioning group for the great efforts made during the commissioning.



Thanks for your attentions!!