中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Reliability and fault-tolerance strategy in CADS linac and beam commissioning of CADS injector-I

4th Workshop on ADS and Thorium

University of Huddersfield, UK

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Outline

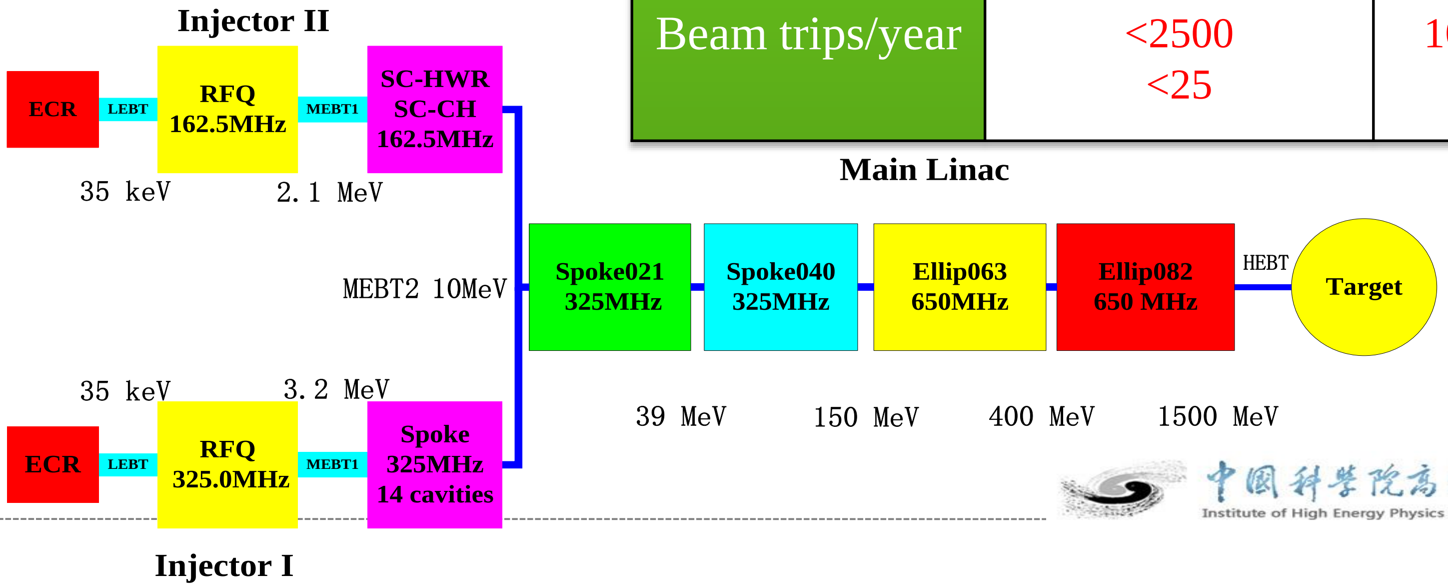
- Introduction: CADS linac
- Linac design
- Beam loss prediction
  - Errors analysis
  - Mismatch study
- Compensation–rematch of major element failures
  - Method study
  - Procedures discussion
- Beam commissioning of CADS injector-I
- Summary

1. Introduction: C-ADS

The **C-ADS** (**C**hina **A**ccelerator-**D**riven **S**ubcritical **S**ystem) project is a strategic plan to solve the nuclear waste and resource problems for nuclear energy in China.

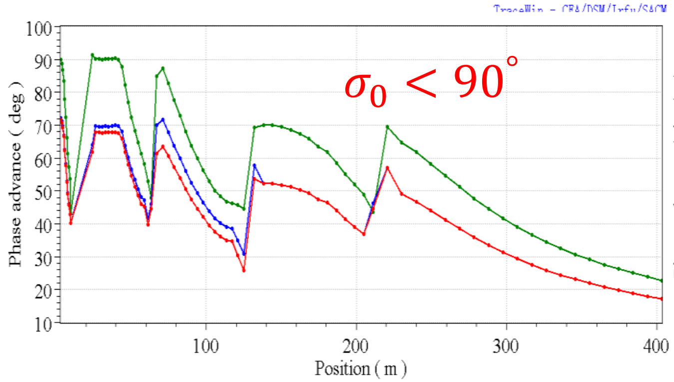
- **CW proton** linac
- **Superconducting** acceleration structures except the RFQs
- HWR / Spoke / Elliptical cavity
- **Reliability**
  - Robust design: robust *beam dynamics && all hardware systems* design
  - Redundancy: *tolerate failures*
    - *30% for compensation*
  - Repair ability

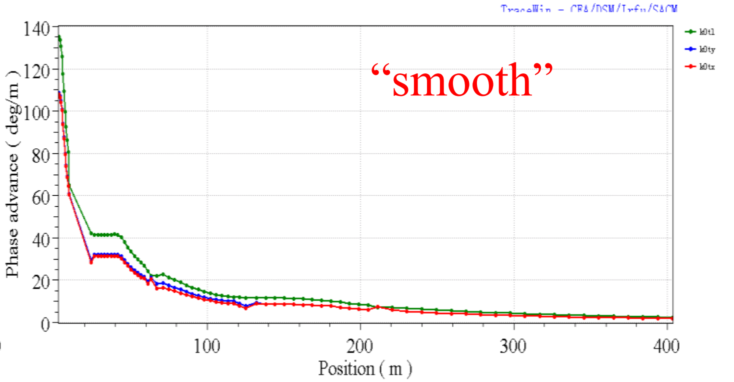
Particle	Proton	
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
RF frequency	(162.5)/325/650	MHz
Duty factor	100	%
Beam Loss	<1	W/m
Beam trips/year	<25000 <2500 <25	1 s<t<10 s 10 s<t<5 m t >5 m

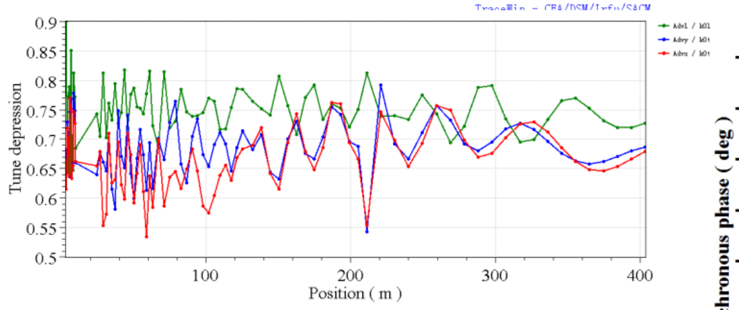


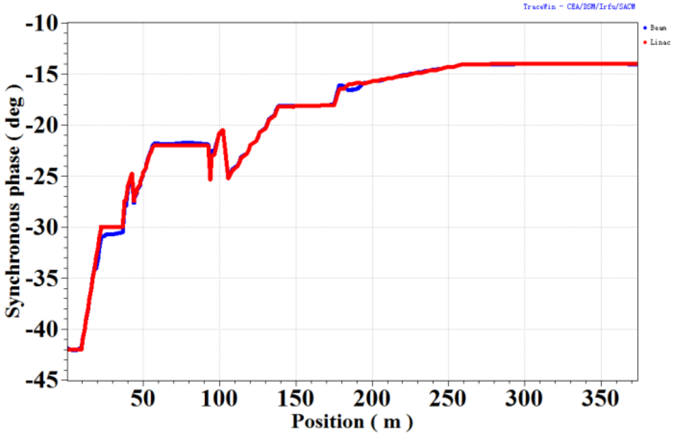
2. Linac design: rules for beam dynamics

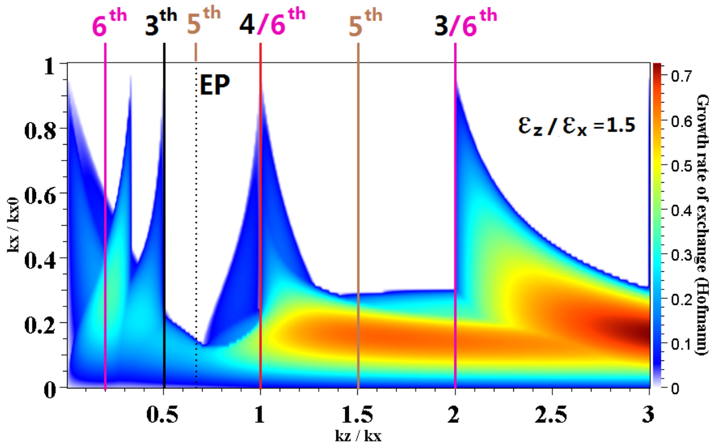
- Keep period phase advance at zero-current $\sigma_0 < 90°$ in all planes to avoid structure and space charge driven resonances: **envelope instability or 4th order resonances;**
- Keep "smooth" phase advance and provide good matching between sections in all planes to minimise emittance growth: *balance E_{acc} and phase advance*
- Keep $\sigma_L \approx 1.25\ \sigma_T$ to stay away from the dangerous parametric resonance $\sigma_T = \sigma_L/2$ and avoid emittance exchange between transverse and longitudinal planes via space charge;
- Keep tune depression >0.5 to avoid SC-driven resonances & instabilities
- Low enough synchronous phases to get large longitudinal acceptance







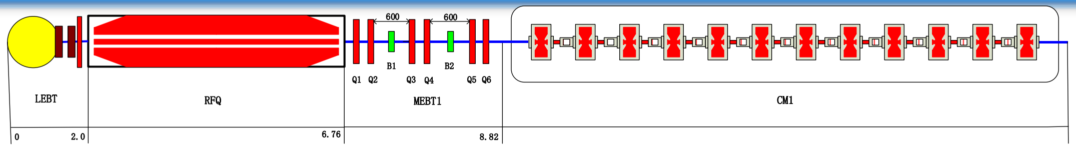


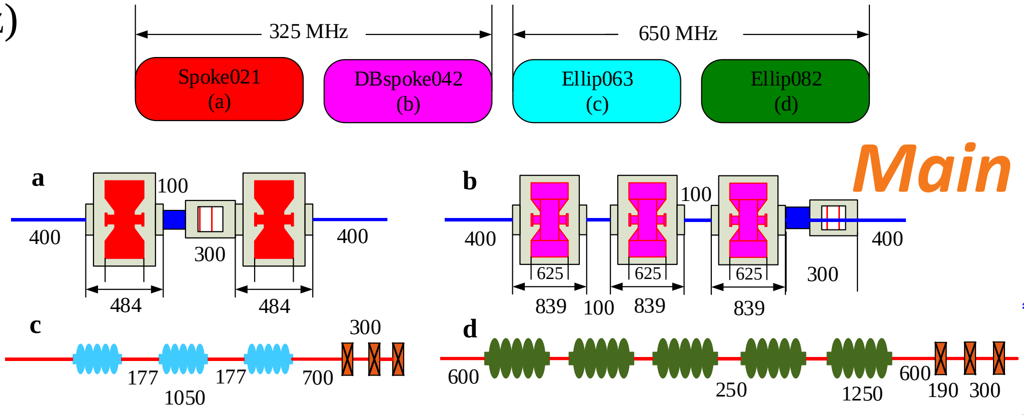


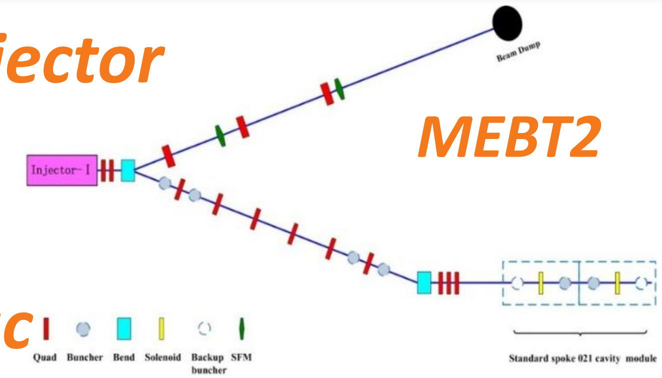
$$\sigma_{l0} = \sqrt{LP}k_{l0} = \sqrt{-\frac{2\pi E_0 TL \sin(\varphi_s) P}{mc^2 (\beta\gamma)^3 \lambda}}$$

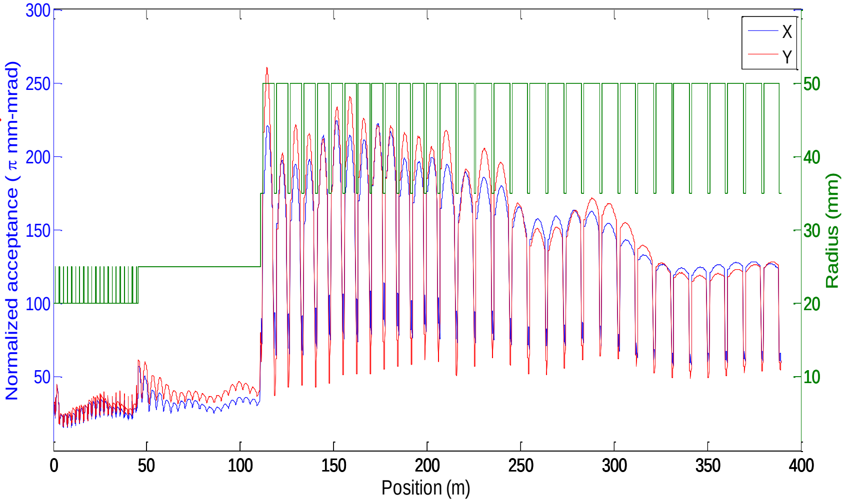
2. Linac design: Accelerating structure

- Injector
  - ECR-IS
  - RFQ (162.5 MHz/ 325 MHz)
  - Spoke012/HWR009
- Main linac
  - Spoke021
  - Spoke040
  - Ellip063
  - Ellip082







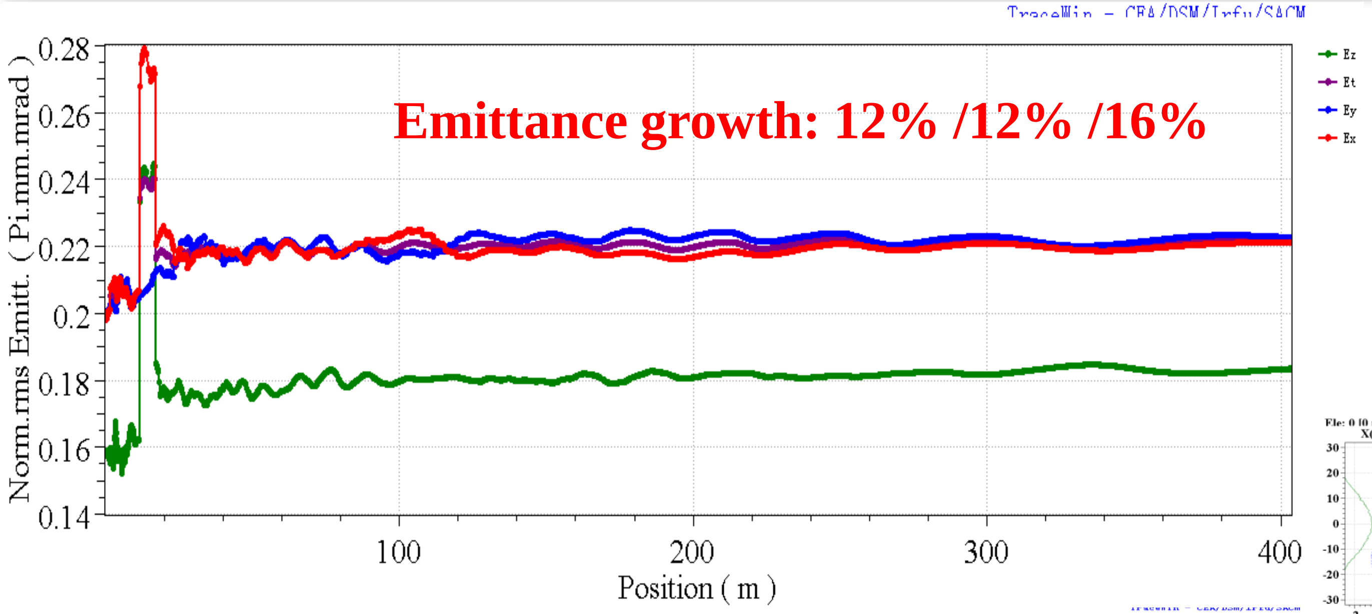


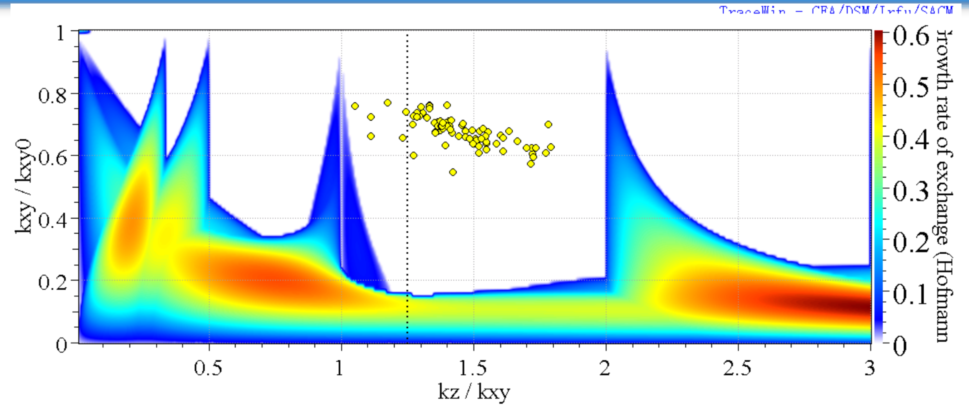
	RFQ	Spoke012	Spoke021	Spoke040	Ellip063	Ellip082	Total
Energy (MeV)	3.2	10	38	149	399	1504	1504
Cavity no.	1	14	36	60	42	100	252
Focusing structure		RS	RSR	R^2SR^2	R^3FDF	R^5FDF	
CM no.		2	6	15	14	20	57
Synch. phase		-35~-25	-42~-30	-27~-22	-20~-18	-15~-14	
Section leng. (m)		10.006	39.024	57.84	84.336	191.8	383

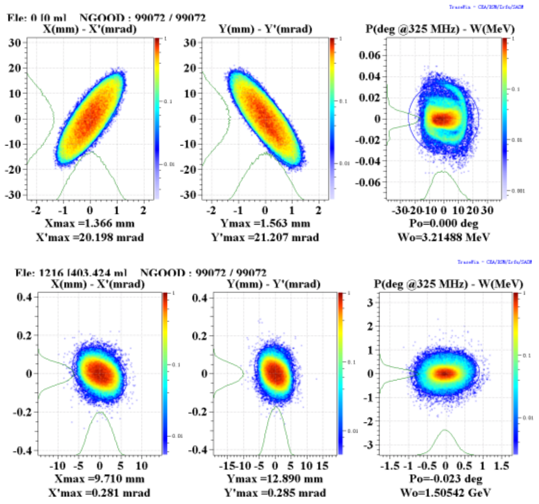
- ✓ **Transverse acceptance:**
  - ✓ Aperture / RMS envelope > **10**
  - ✓ Acceptance.CM/Acceptance.RT > **2**

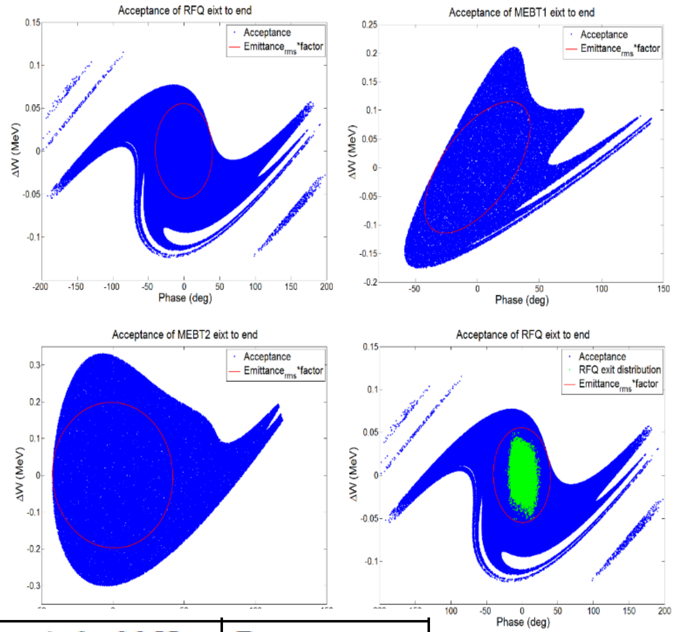
2. Linac design: Beam dynamics simulation

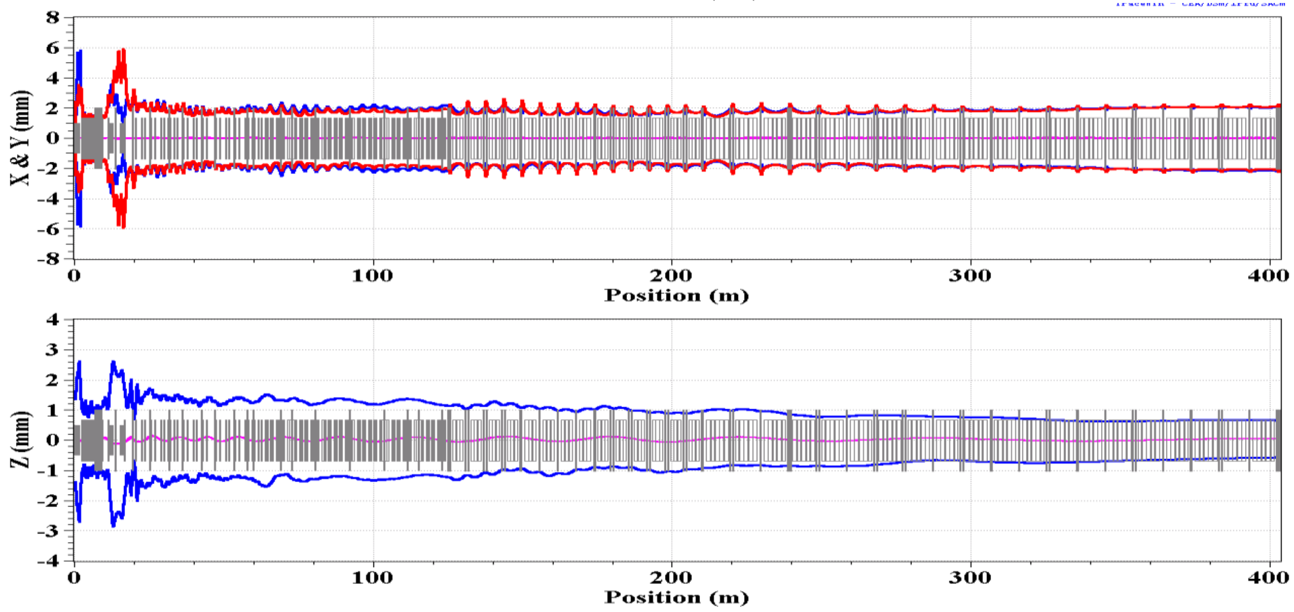
ADS proton linac











	Rms emittance ε_r (π deg.MeV)	Factor (Acceptance/ε_r)
RFQ exit to end	0.0582	38
MEBT1 exit to end	0.0583	66
MEBT2 exit to end	0.0696	120

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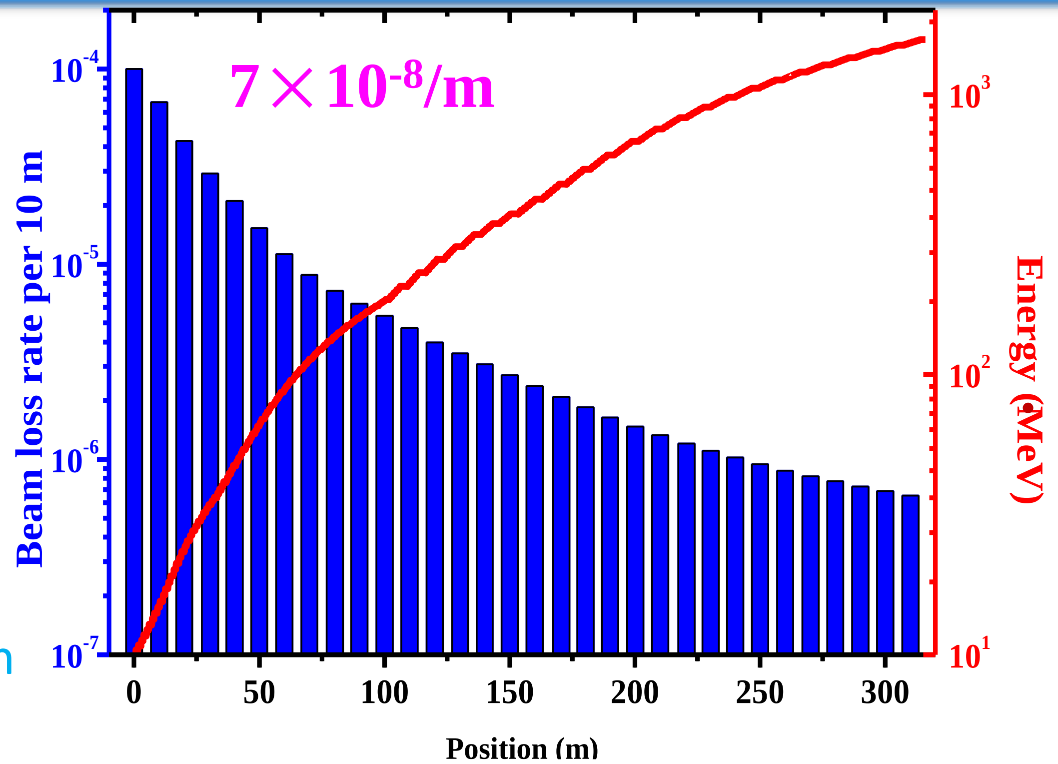
3. Beam loss prediction: Beam loss mechanism

- Fortunately, **Proton**
- **Emittance growth**
  - Non-linear space charge
  - Resonances
  - Anisotropy
  - Instability
  - ***Mismatch***
  - Initial density profile mismatch
  - …
- ***Random errors***
- ***Beam outside bucket***
  (longitudinal acceptance)



***H^-* only**

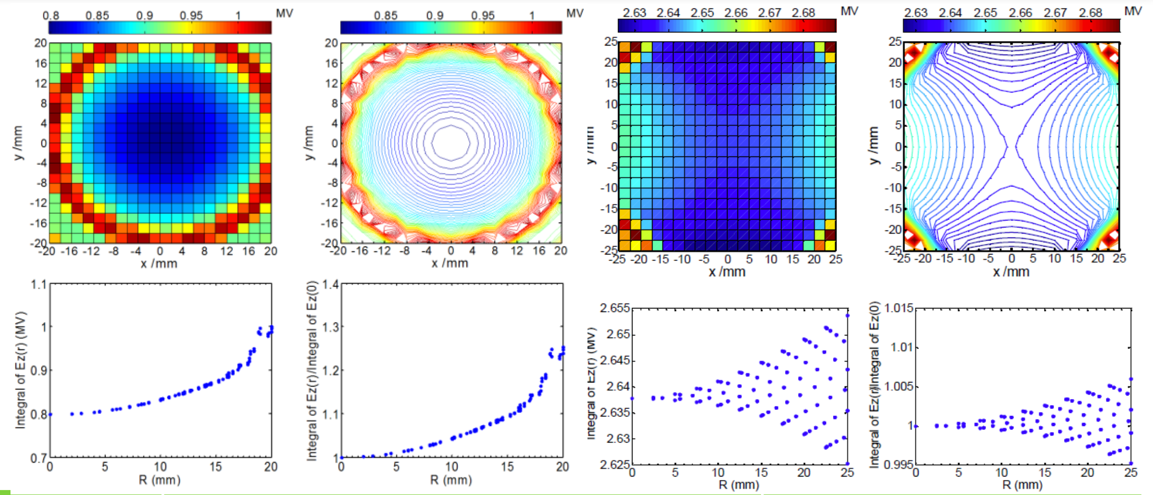
- Intra-beam stripping
- Residual gas stripping
- Field stripping
- H^+ capture and acceleration
- and so on

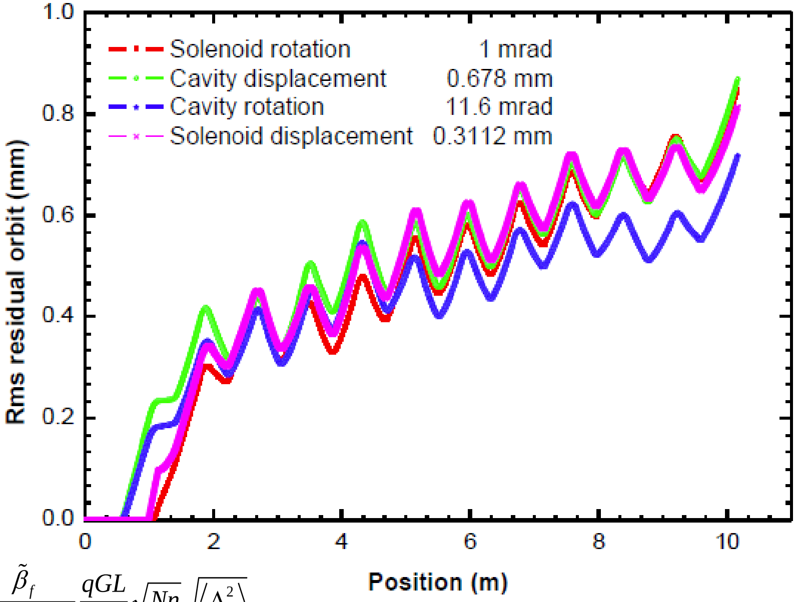
✓ Errors analysis
- ✓ *Misalignment*
- ✓ *Field errors*

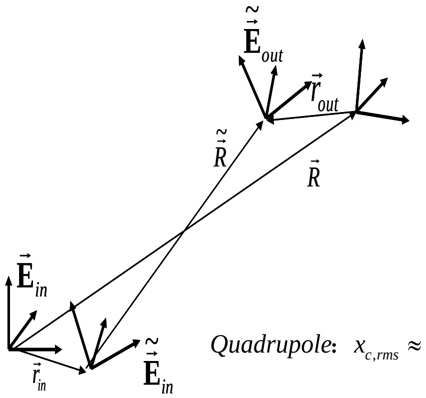
✓ Mismatch study
- ✓ *Mismatch in one plane*
- ✓ *Mismatch in coupling*

3. Beam loss prediction: Errors analysis (1)

- Error analysis
  - Misalignment
    - All elements
    - Residual orbit && Correction
    - Cavity field & asymmetry (spoke cavity)
  - Field error
    - Magnet
    - Cavity







Error No.	Error description		Tolerance Static	Tolerance Dynamic
1	Magnetic element displacement (mm)	Quadrupole	0.1	0.002
		Solenoid (cold)	1	0.01
		Bending magnet	0.5	0.005
2	Magnetic element rotation (mrad)		2	0.02
3	Magnetic element field (%)		0.5	0.05
4	Cavity displacement (cold) (mm)		1	0.01
5	Cavity rotation (mrad)		2	0.02
6	RF amplitude fluctuation (%)		1	0.5
7	RF phase fluctuation (°)		1	0.5
8	BPM uncertainty (mm)		0.1	
9	Bending magnet field error (%)		0.1	0.01

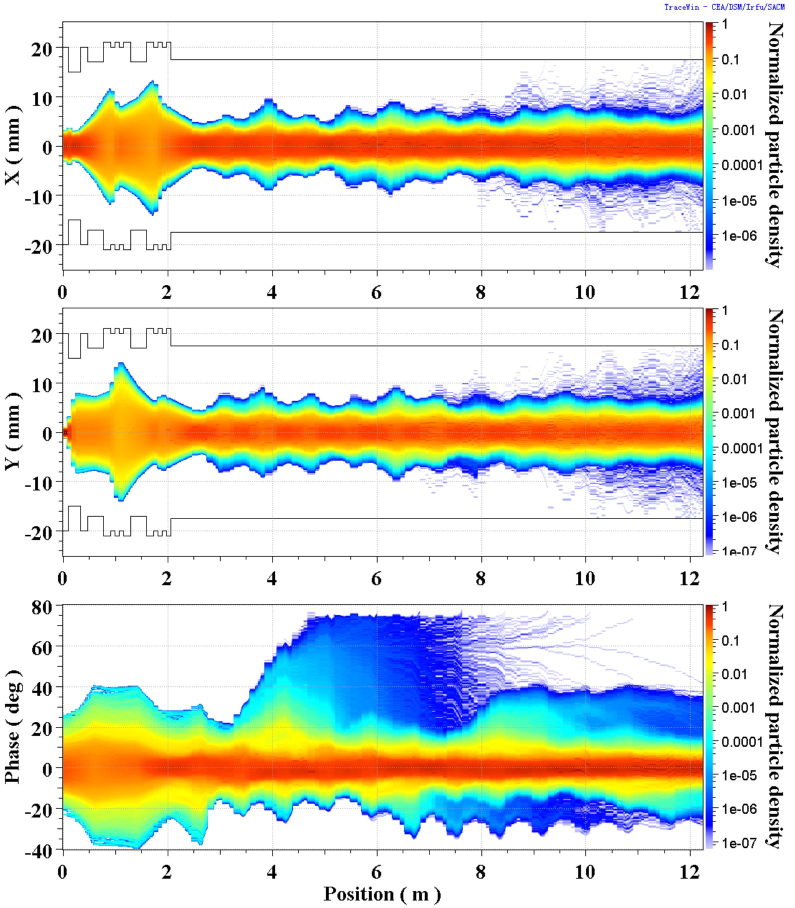
Quadrupole: $x_{c,rms} \approx \frac{\tilde{\beta}_f}{2(1+\tilde{\alpha}_f^2)}\frac{qGL}{P_f}\sqrt{Nn}\sqrt{\langle\Delta^2\rangle}$

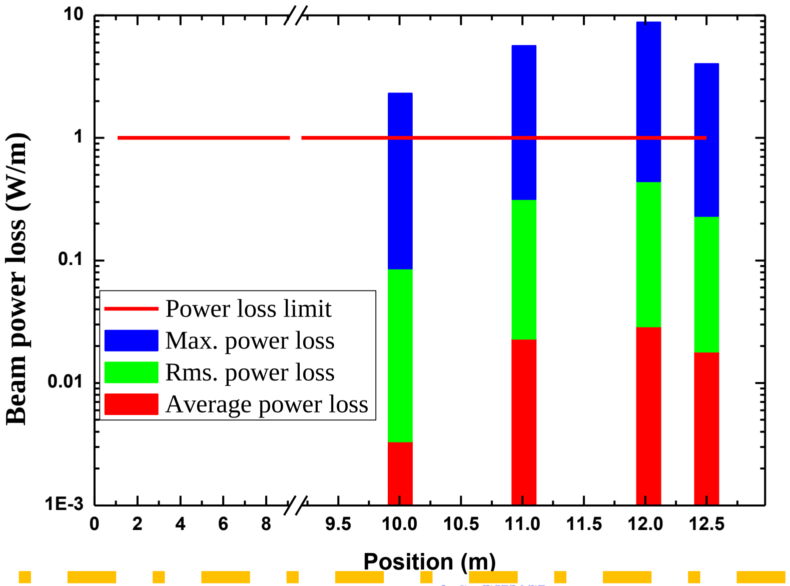
Solenoid: $x_{c,rms} \approx \frac{\tilde{\beta}_f}{2(1+\tilde{\alpha}_f^2)}\sqrt{\left(\frac{qBL}{2}\right)^2\frac{N}{P_fP_0}\sqrt{\left(\frac{qB}{2P_f}\right)^2\langle\Delta^2\rangle+\left(\frac{P_0}{P_f}+\frac{L^2}{4}\left(\frac{qB}{2P_f}\right)^2\right)\langle\phi^2\rangle}}$

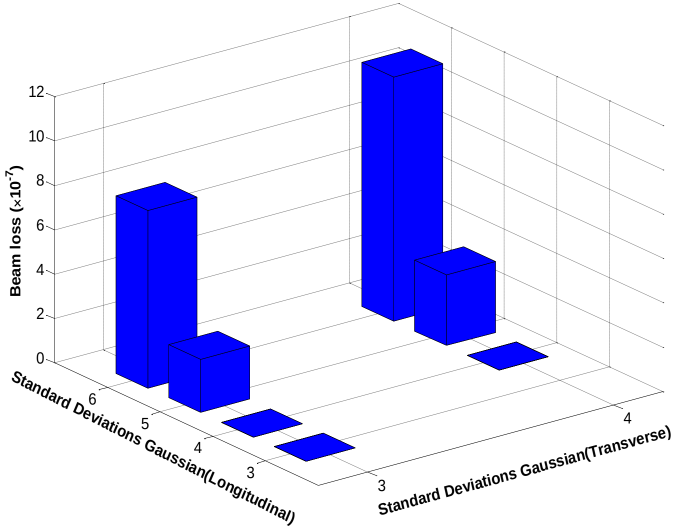
Cavity: $x_{c,rms} \approx \frac{\tilde{\beta}_f}{2(1+\tilde{\alpha}_f^2)}\frac{1}{\beta_f\gamma_f}\sqrt{\sum_i\left(\frac{q\pi E_0TL_s\sin(\varphi_s)}{mc^2(\beta\gamma)^2\lambda}\right)_i^2\left(\langle\Delta x^2\rangle+f_i^2\langle\phi_y^2\rangle\right)},\quad f=\frac{\beta\gamma^2\lambda}{|\pi\tan(\varphi_s)|}$

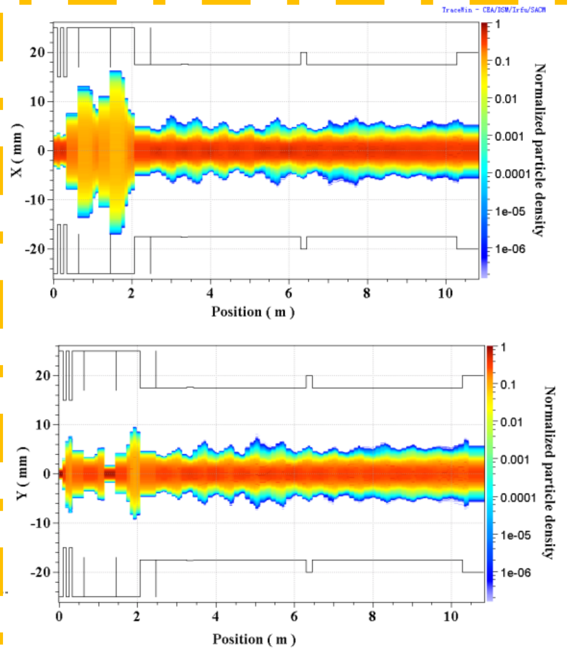
3. Beam loss prediction: Errors analysis (2)

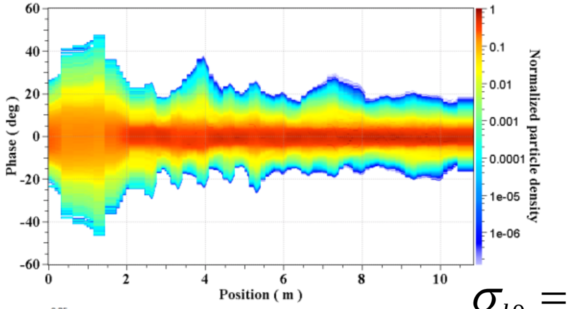
- Injector-I as an example

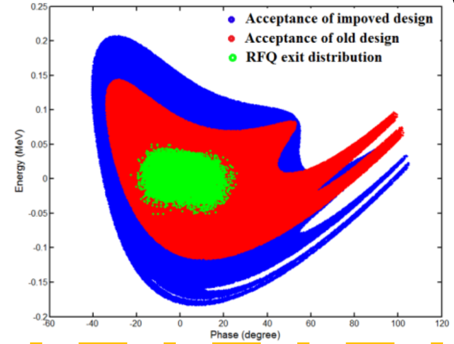












$$\sigma_{l0} = \sqrt{LPk_{l0}} = \sqrt{-\frac{2\pi E_0 TL\sin(\varphi_s) P}{mc^2(\beta\gamma)^3\lambda}}$$

Solenoid total length: 300 mm-> 150 mm

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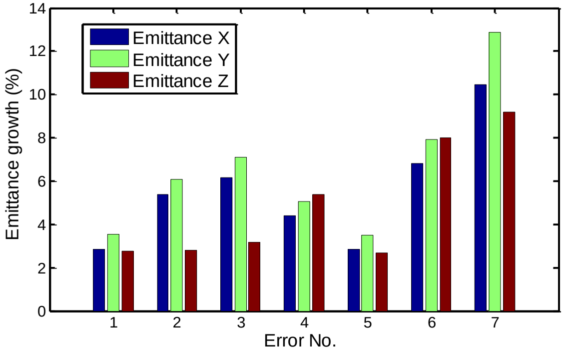
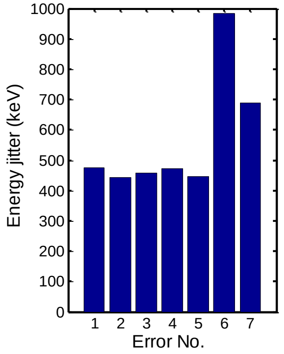
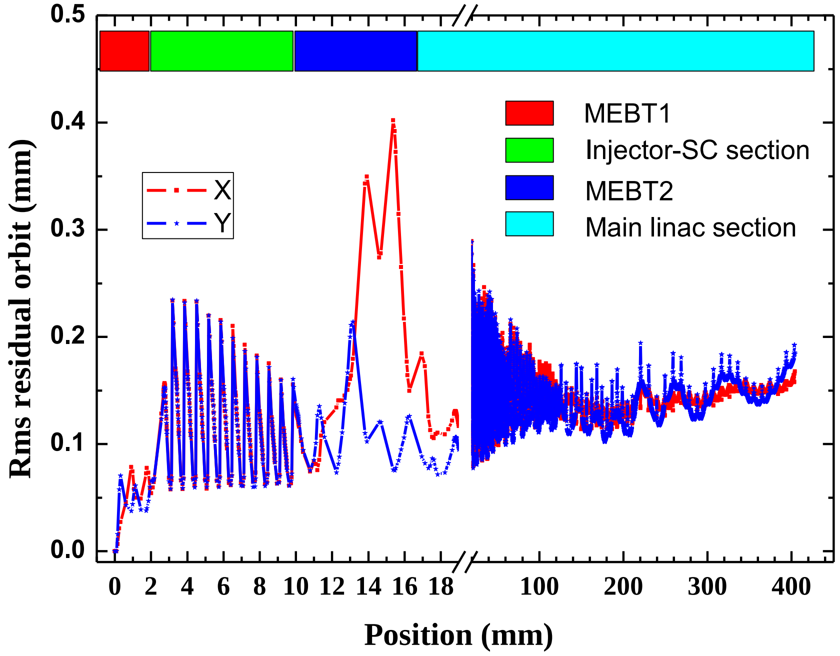
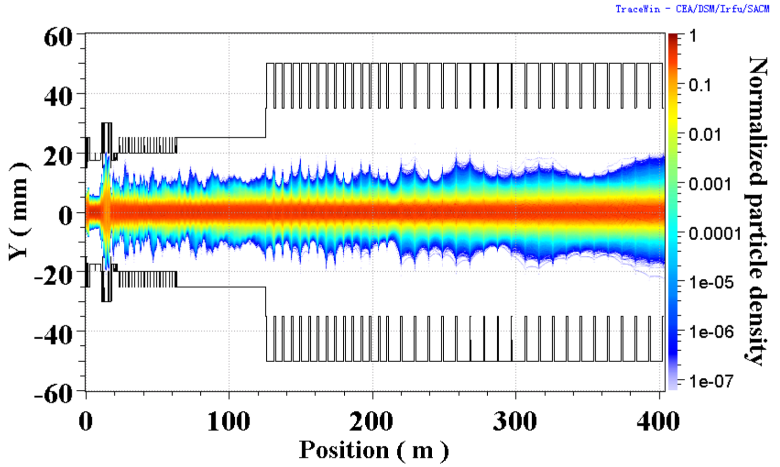
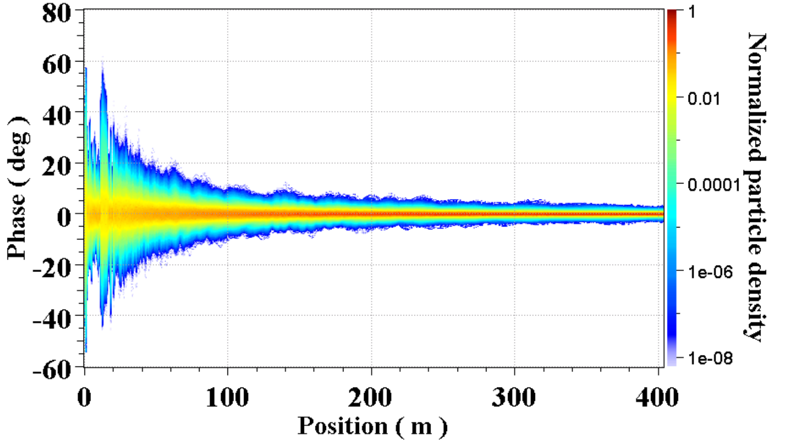
3. Beam loss prediction: Errors analysis (3)

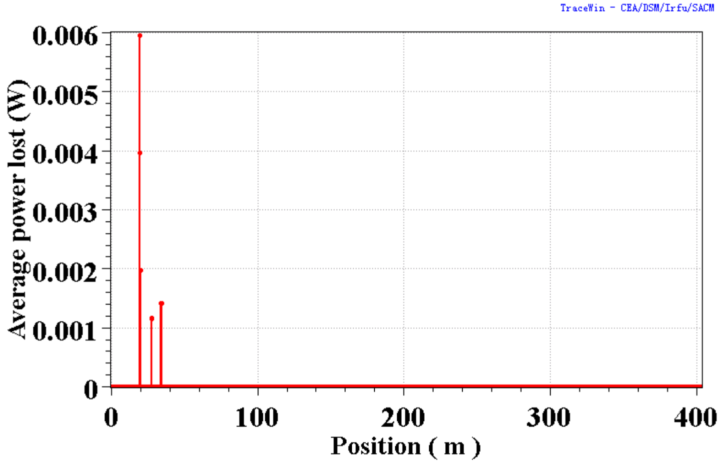


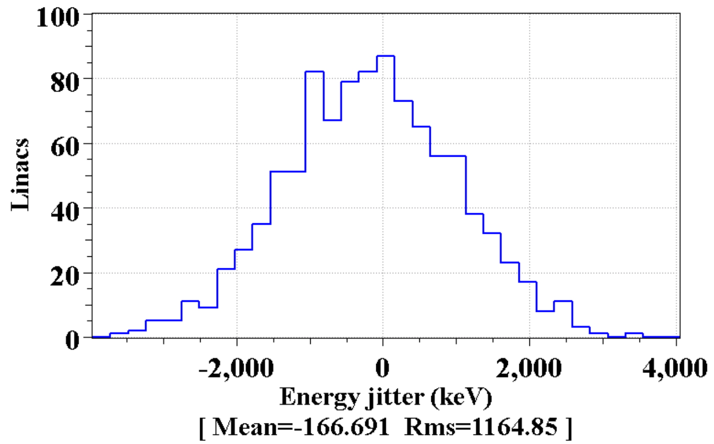








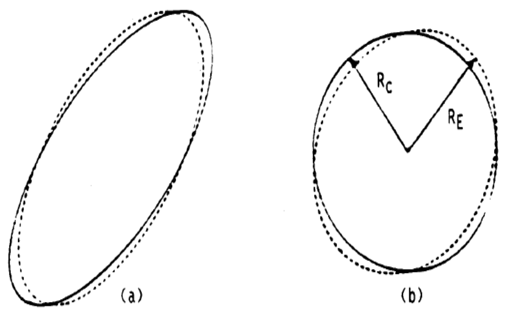




	Ex (%) (rms)	Ey (%) (rms)	Ez (%) (rms)	Energy jitter (keV)	Beam loss
无误差	11.8	12.0	15.3	0	0
有误差有校正	34.8(11.0)	37.1(12.7)	33.7(11.9)	1165	1.6×10^{-7}

3. Beam loss prediction: Mismatch study

Mismatch defined



$$\tilde{\gamma}_m x^2 + 2\tilde{\alpha}_m x x' + \tilde{\beta}_m x'^2 = \varepsilon_m$$

$$\tilde{\gamma} x^2 + 2\tilde{\alpha} x x' + \tilde{\beta} x'^2 = \varepsilon$$

$$\Delta = \tilde{\beta}_m \tilde{\gamma} + \tilde{\gamma}_m \tilde{\beta} - 2\tilde{\alpha}_m \tilde{\alpha}$$

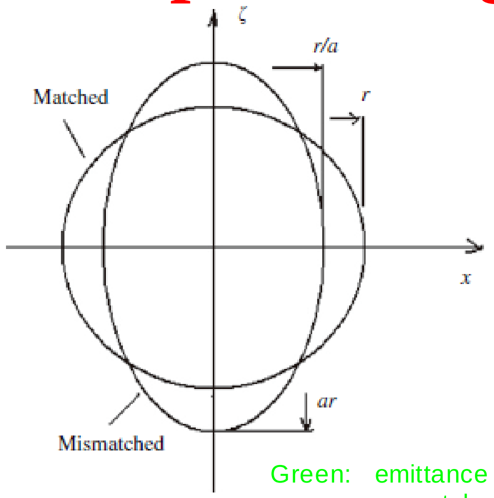
$$M = R_E / R_C - 1 = \sqrt{\frac{\Delta + \sqrt{\Delta^2 - 4}}{2}} \sqrt{\frac{\varepsilon}{\varepsilon_m}} - 1$$

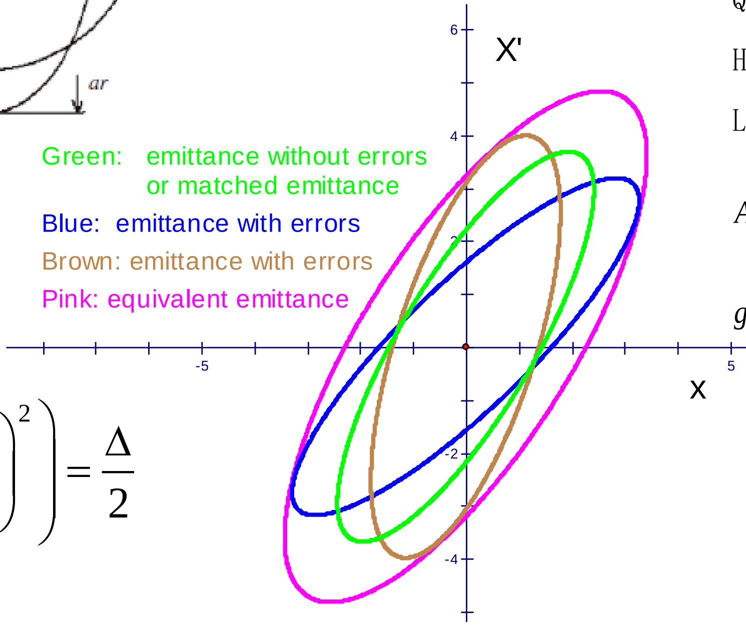
$$\xi = \frac{\varepsilon_{rms,mis}}{\varepsilon_{rms,m}} = \frac{1}{2}\left(\frac{\tilde{\beta}_m}{\tilde{\beta}} + \frac{\tilde{\beta}}{\tilde{\beta}_m} + \frac{\tilde{\beta}_m}{\tilde{\beta}}\left(\tilde{\alpha} - \frac{\tilde{\beta}}{\tilde{\beta}_m}\tilde{\alpha}_m\right)^2\right) = \frac{\Delta}{2}$$

$$\eta = \frac{\varepsilon_{mis}}{\varepsilon_m} = \xi + \sqrt{\xi^2 - 1} = (1 + M)^2$$

Filamentation effect

Space charge





$$\frac{d^2 a_x}{ds^2} + k_{t0}^2 a_x - \frac{\varepsilon_t^2}{a_x^3} - \frac{K_t}{a_y b} = 0$$

$$\frac{d^2 a_y}{ds^2} + k_{t0}^2 a_y - \frac{\varepsilon_t^2}{a_y^3} - \frac{K_t}{a_x b} = 0$$

$$\frac{d^2 b}{ds^2} + k_{l0}^2 b - \frac{\varepsilon_l^2}{b^3} - \frac{K_l}{a_x a_y} = 0$$

Quadrupole mode $\sigma_{env,Q} = 2\sigma_t$, $\Delta a_x/a = -\Delta a_y/a = A_m \cos(\sigma_{env,Q}\, s/L + \phi)$, $\Delta b/b = 0$

High mode $\sigma_{env,H}^2 = A + B$, $\Delta a_x/a = \Delta a_y/a = g_H \Delta b/b = A_m \cos(\sigma_{env,H}\, s/L + \phi)$

Low mode $\sigma_{env,L}^2 = A - B$, $\Delta a_x/a = \Delta a_y/a = g_L \Delta b/b = A_m \cos(\sigma_{env,L}\, s/L + \phi)$

$$A = \sigma_{t0}^2 + \sigma_t^2 + \frac{1}{2}\sigma_{l0}^2 + \frac{3}{2}\sigma_l^2, \quad B = \sqrt{\left(\sigma_{t0}^2 + \sigma_t^2 - \frac{1}{2}\sigma_{l0}^2 - \frac{3}{2}\sigma_l^2\right)^2 + 2\left(\sigma_{t0}^2 - \sigma_t^2\right)\left(\sigma_{l0}^2 - \sigma_l^2\right)}$$

$$g_{H/L} = \frac{\sigma_{t0}^2 - \sigma_t^2}{\sigma_{env,H/L}^2 - 2\left(\sigma_{t0}^2 + \sigma_t^2\right)}$$

$$\frac{\sigma_{t,l}^p}{\sigma_{env}} = \frac{n}{m} = \frac{1}{2}, \frac{1}{3} \ldots$$

$$\sigma_t \le \sigma_t^p \le \sigma_{t0}$$

$$\sigma_l \le \sigma_l^p \le \sigma_{l0}$$

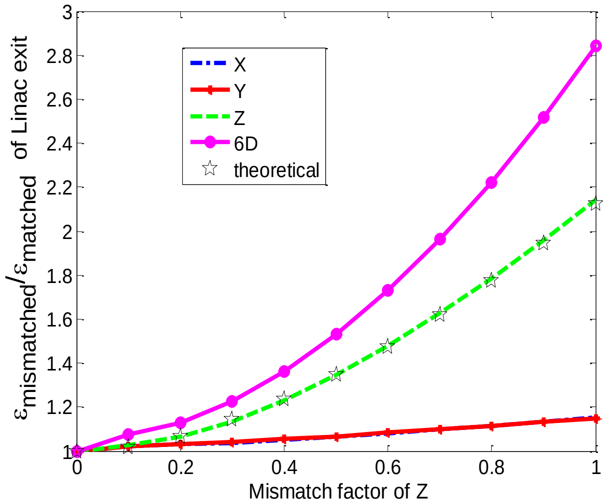
$$38^\circ \le \sigma_{\mathrm{env,H}} \le 155^\circ$$

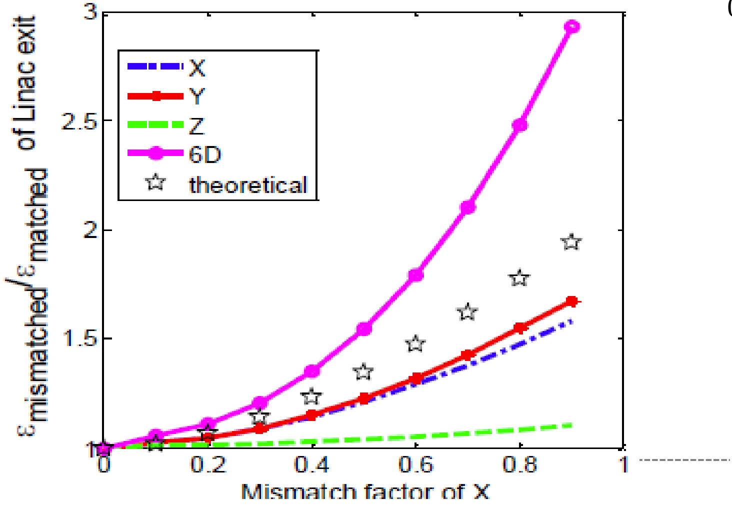
$$27^\circ \le \sigma_{\mathrm{env,L}} \le 107^\circ$$

3. Beam loss prediction: Mismatch study

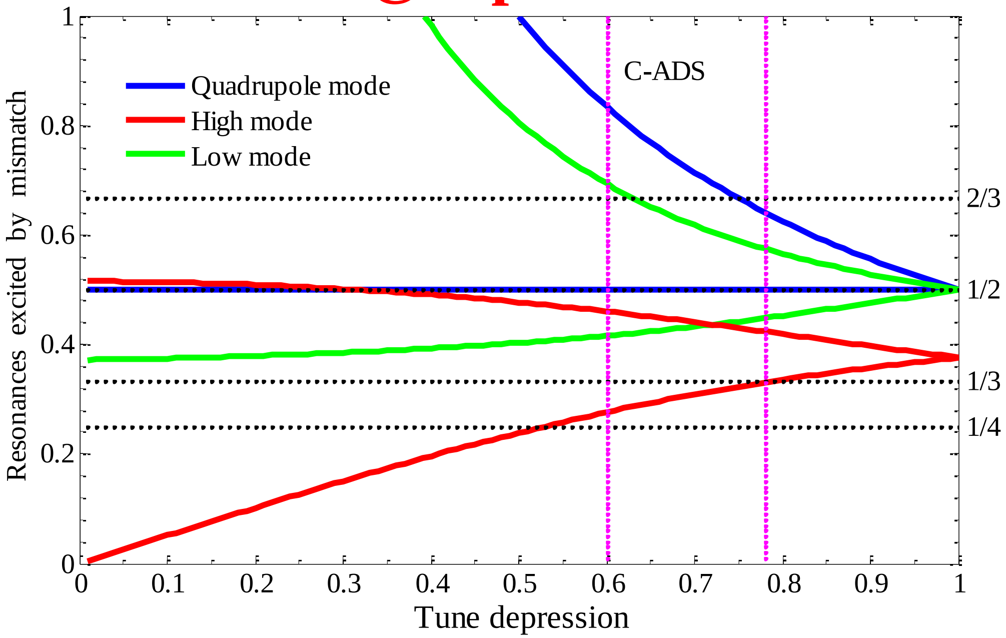
ADS proton linac

Filamentation effect @ one plane

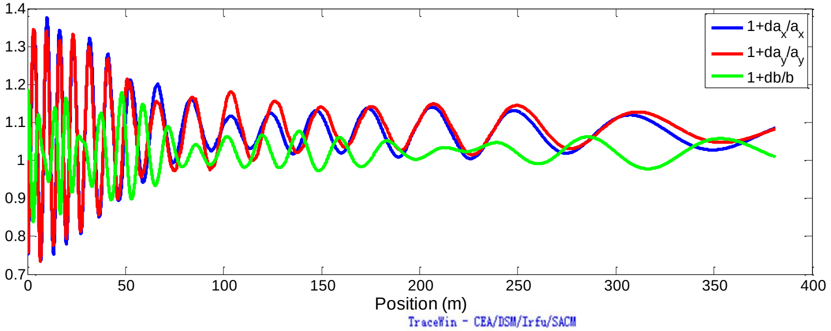


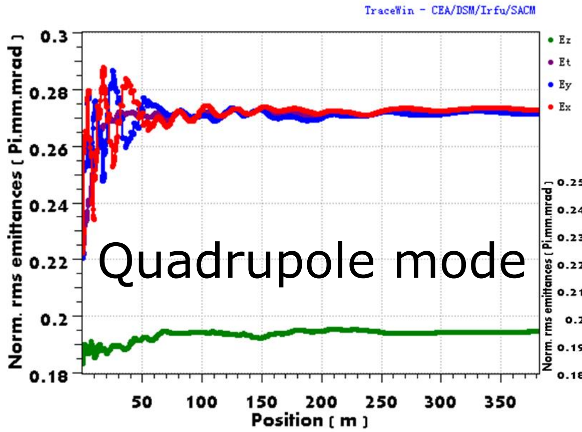


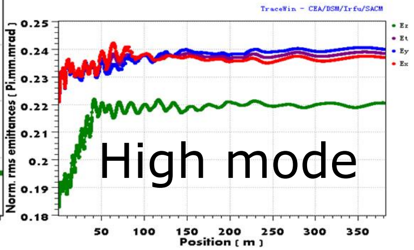
Space charge @ 3 planes

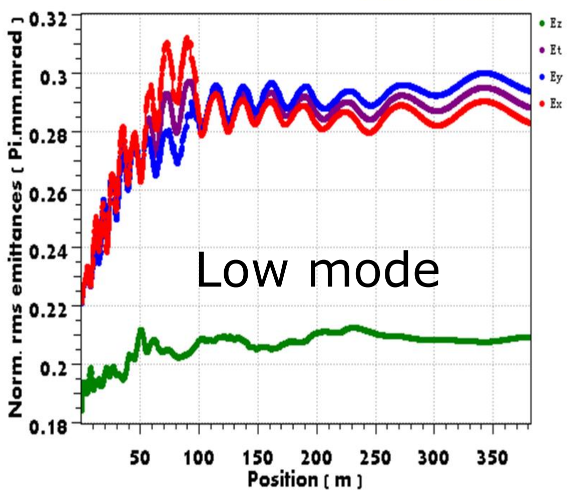


Mode	mismatch factor	Mismatch factor x	Mismatch factor y	Mismatch factor z	Ex %	Ey %	Ez %
Matched	0	0	0	0	2.7	3.2	4.2
Quad.	0.3	+0.3	+0.43	0	23.9	23.3	6.9
High	0.3	+0.08	+0.08	+0.3	7.7	9.0	21.2
Low	0.2	-0.4	-0.4	+0.2	28.5	30.0	15.1









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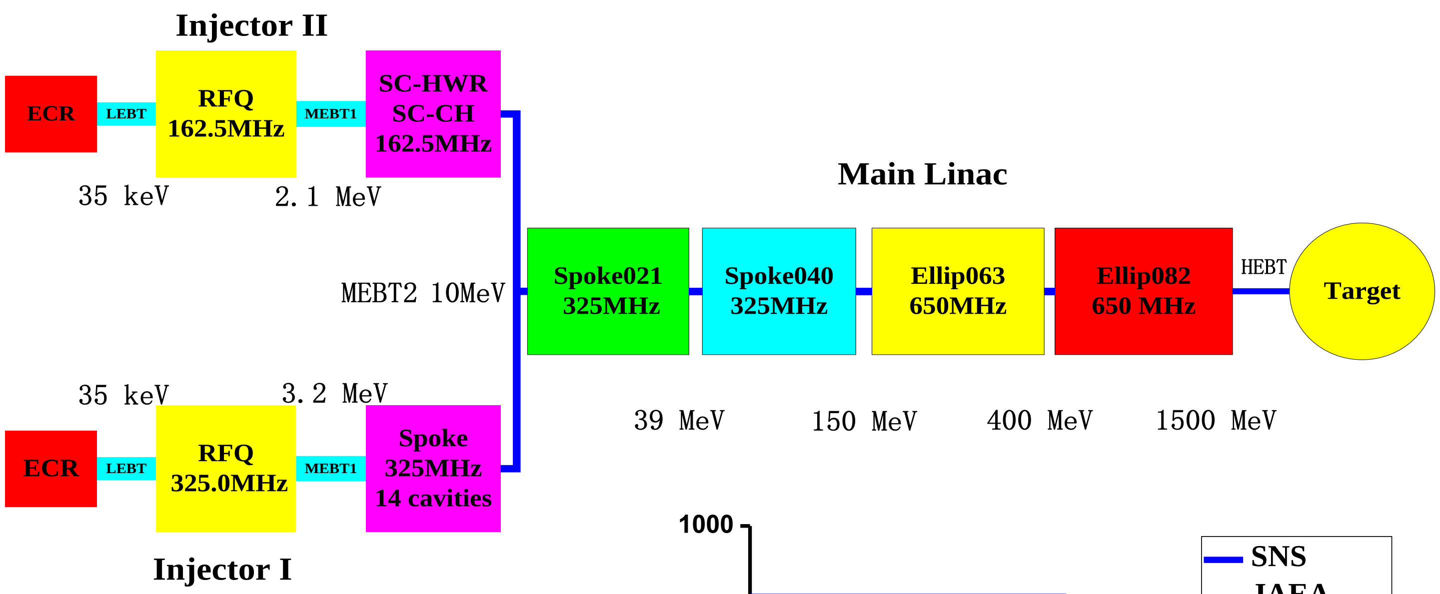
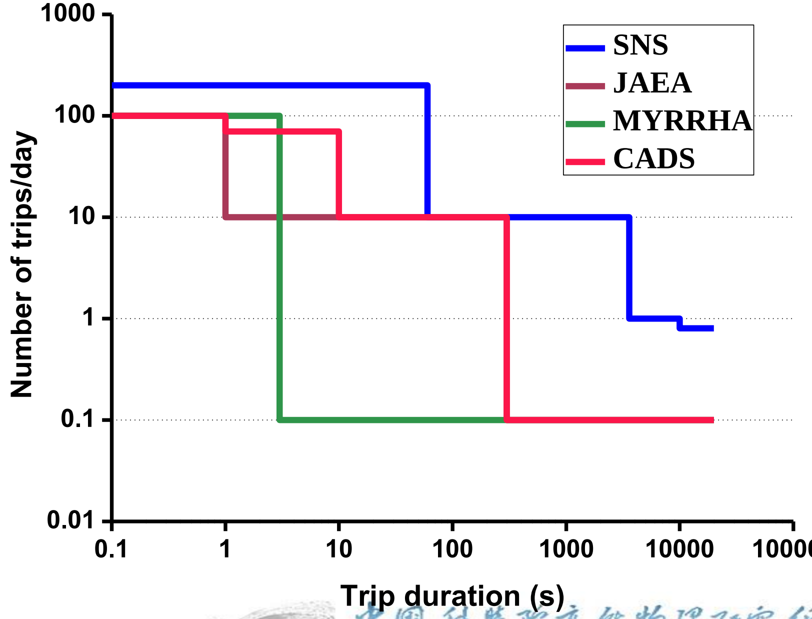
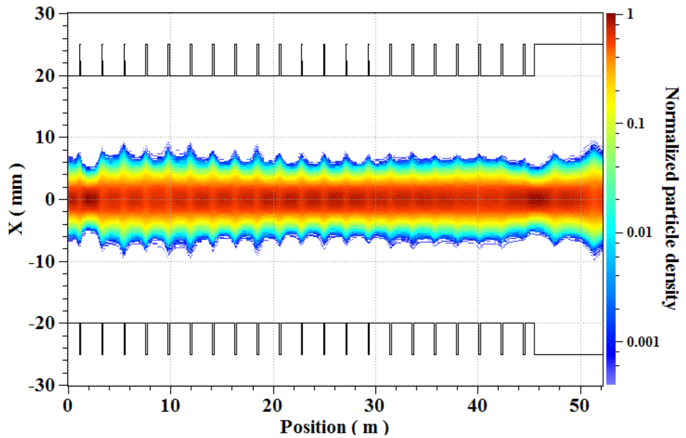
4. Compensation–rematch of major element failures

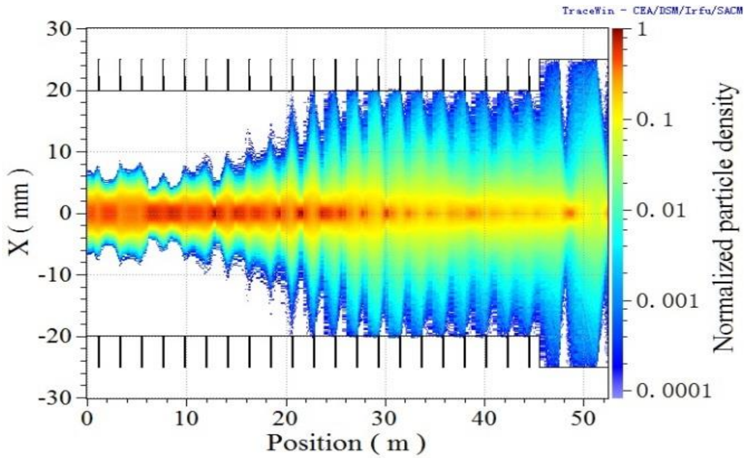
➢ Reliability

- ➢ Redundancy: *tolerate failures*
  - ➢ *30% accelerating gradient for compensation*
- ➢ Injector
  - ➢ “Hot-standby” OR. Parallel
- ➢ Main linac
  - ➢ Local compensation-rematch
  - ➢ Global compensation-rematch





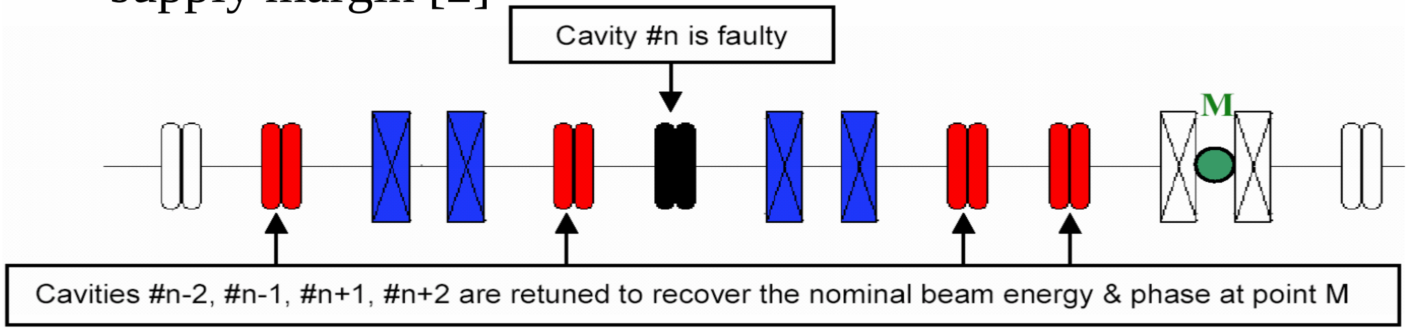




4. Compensation–rematch of major element failures

- Global compensation-rematch
  - Retuning and rephrasing of all following elements, a few minutes [1] (SNS)
  - Lattice update every time
  - Little redundancy, **save cost**
- Local compensation-rematch
  - Independence and locality
  - Retuning and rephrasing of neighbouring elements
  - 30 % accelerating gradient redundancy, ~70% power supply margin [2]

Cost!



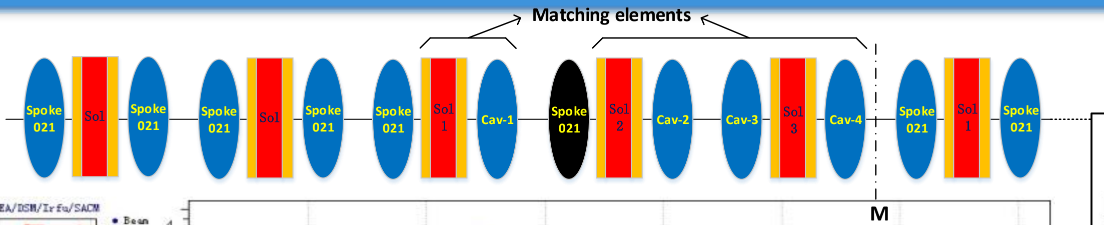
- Larger period phase advance means more difficult to rematch
- Fewer cavities in each period means more difficult to compensation-rematch
- Low energy section is difficult to compensation-rematch

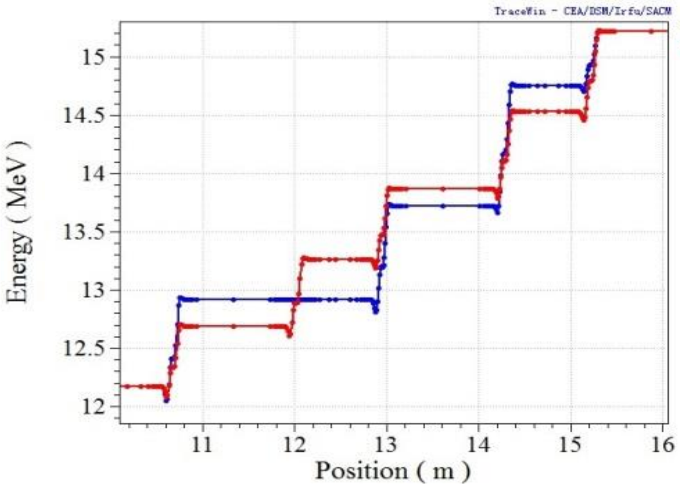
[1] Sang-ho Kim, MO103, Proceedings of LINAC08, Victoria
[2] F. Bouly, et al., MOPP103,Proceedings of LINAC2014, Geneva

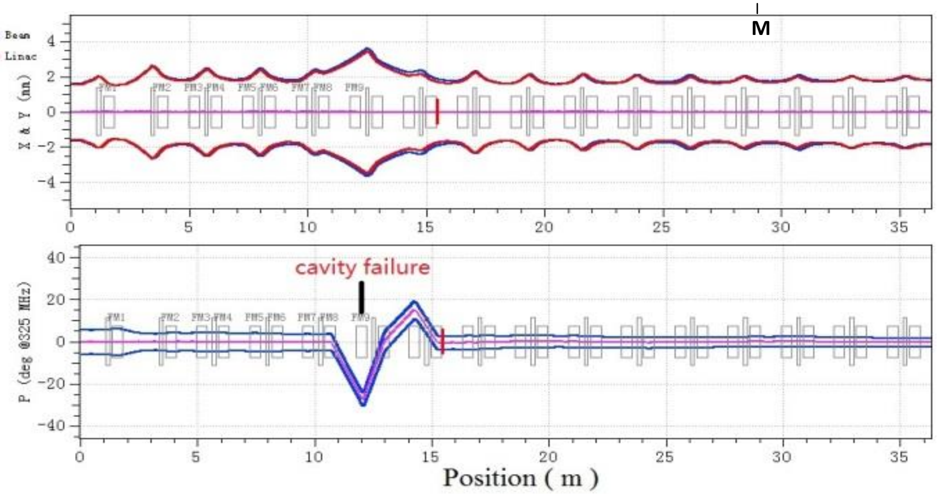
4. Compensation–rematch of major element failures

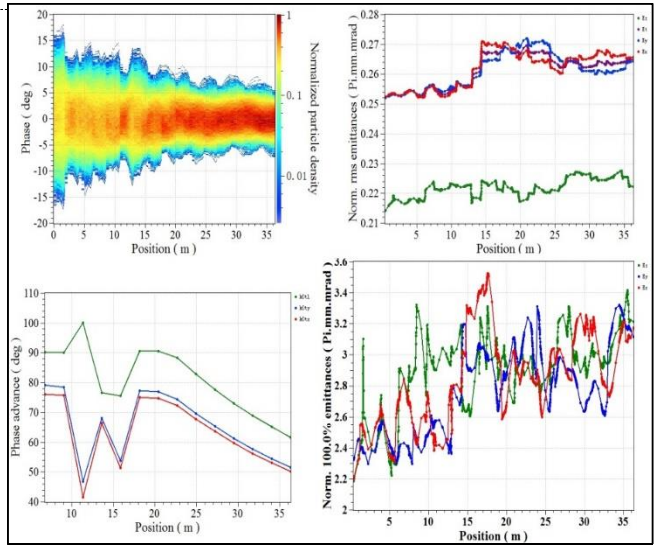
Spoke021 section

@ SUN Biao

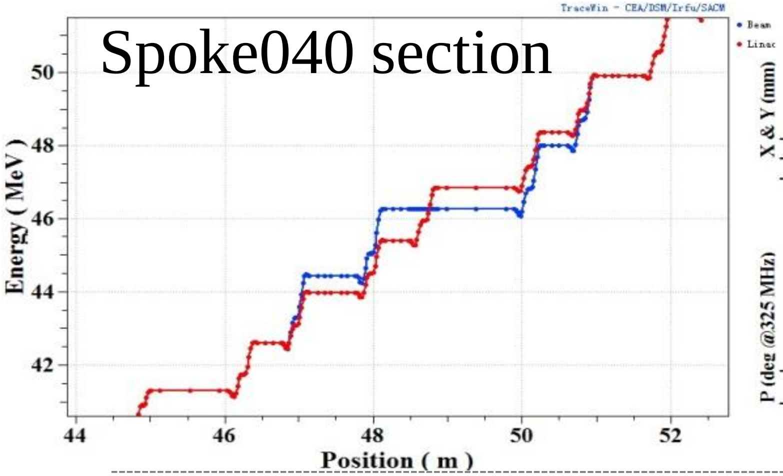


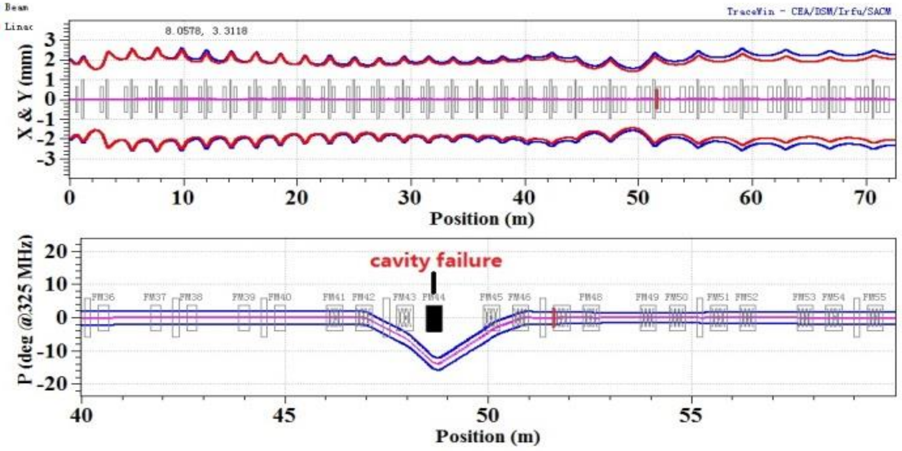


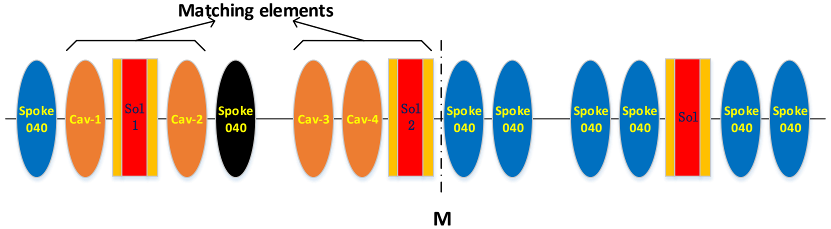


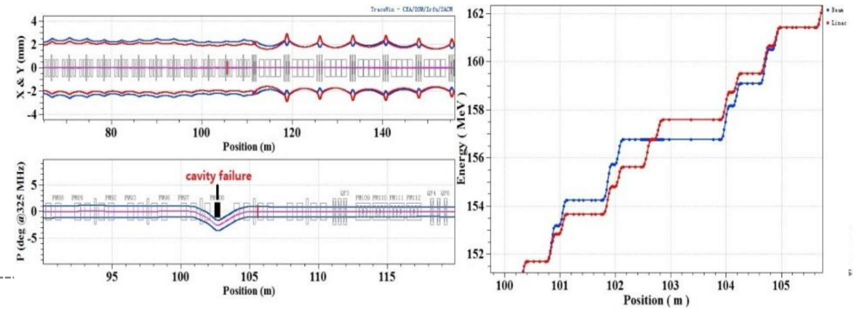


Spoke040 section



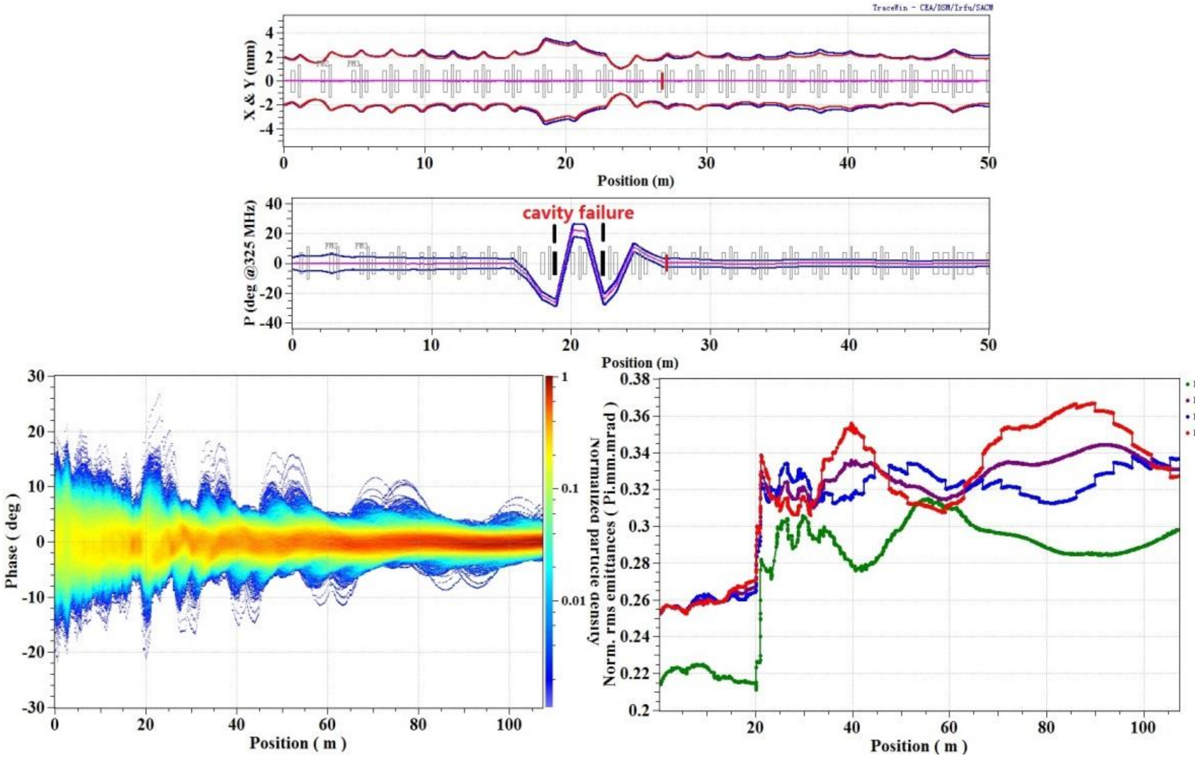






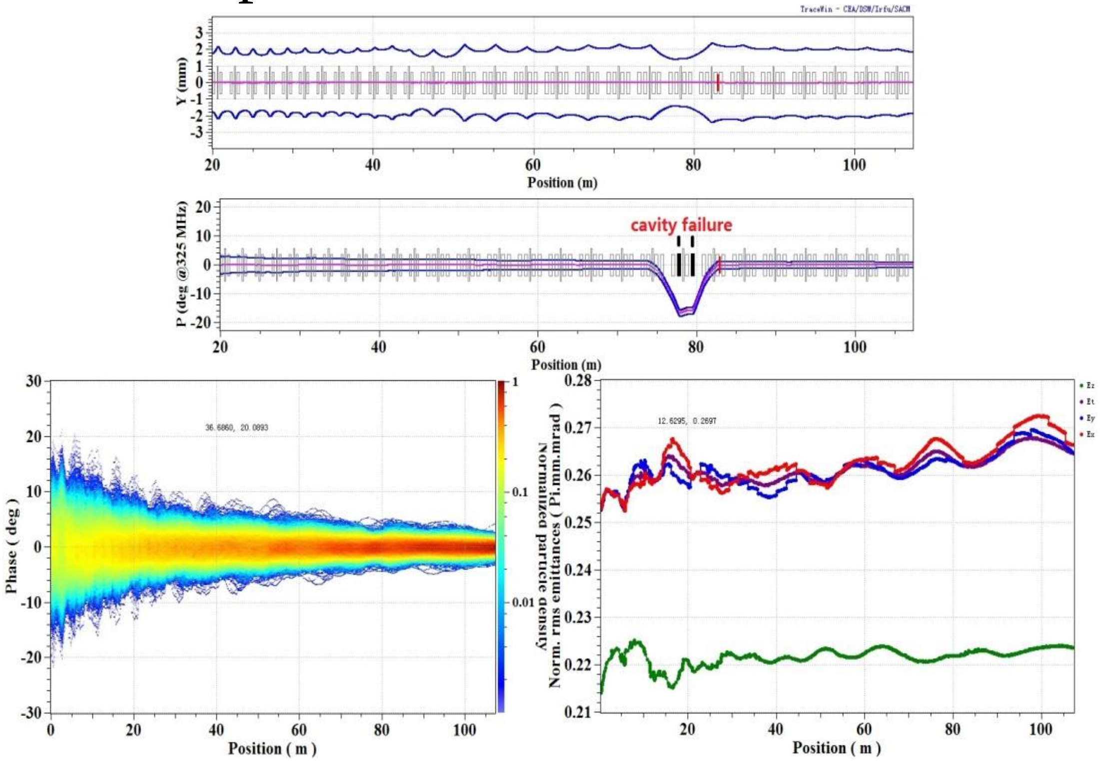
4. Compensation–rematch of major element failures

Spoke021 section



Spoke040 section

@ SUN Biao

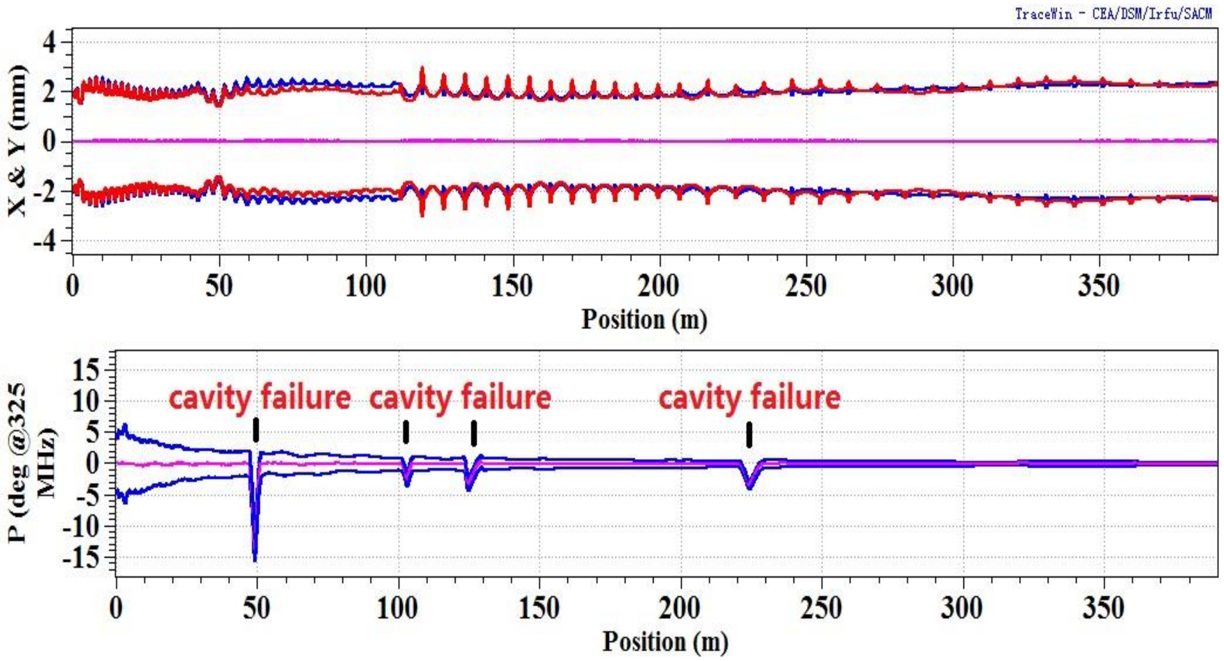


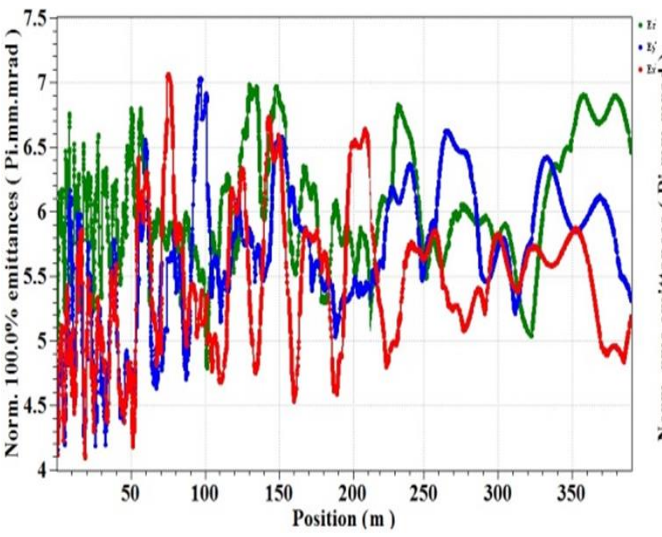
- For spoke021 section and the beginning periods of spoke040 section, if two neighbouring cavities fault, local compensation-rematch method is not well effective, big emittance growth;
- For high energy section, even two neighbouring cavities fault, local compensation-rematch method is effective

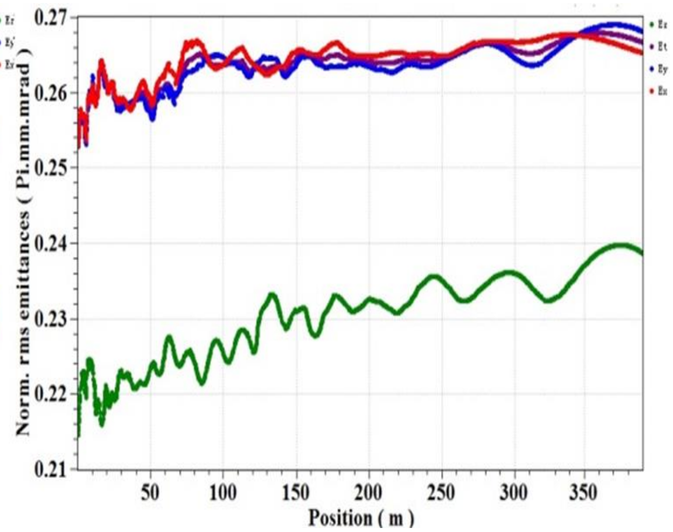
4. Compensation–rematch of major element failures

➢ **Several scenarios studied with multiple cavity failures in different section**

@ SUN Biao



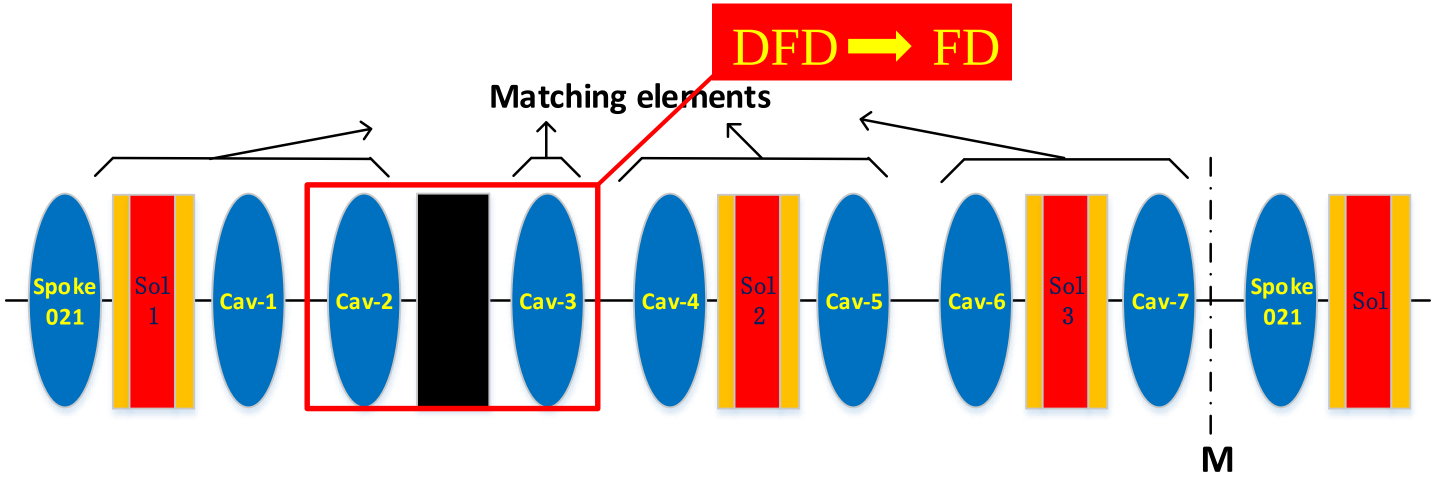




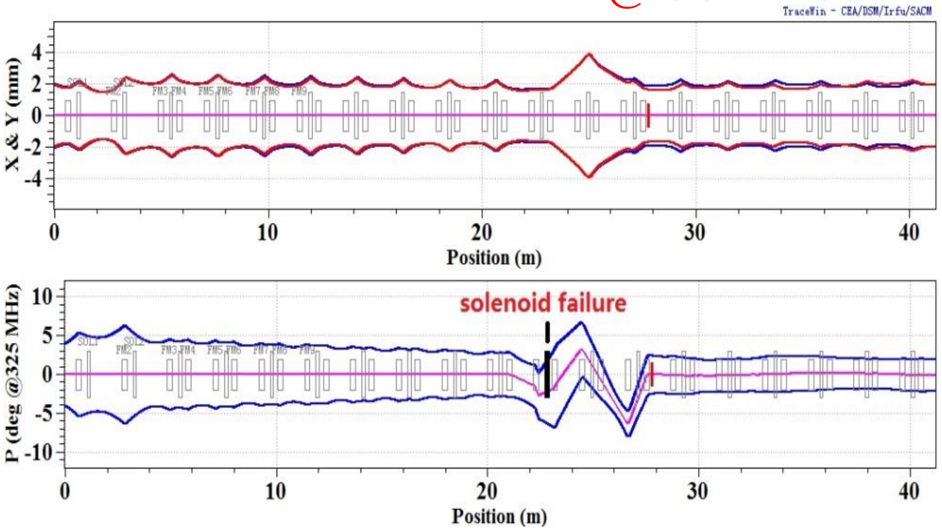
➢ ***The fault recovery scheme is a feasible everywhere in the CADS main linac to compensation-rematch for the loss of a single cavity or even of two neighbouring cavities in high energy section***

4. Compensation–rematch of major element failures

- SC-Solenoid failures in spoke021 section



@ SUN Biao



  - ➢ Reverse first cavity’s synchronous phase to positive value, to help match in transverse plane
  - ➢ Lower second cavity’s synchronous phase to keep the longitudinal acceptance

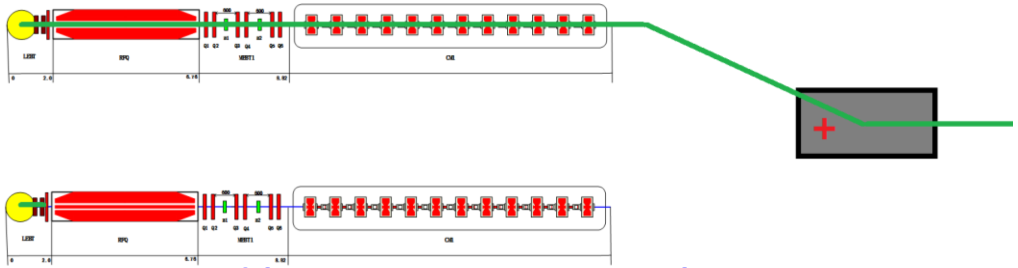
- SC-Solenoid failures in spoke040 section
  - – Just rematch with neighbouring solenoids, no need cavity reverse phase
- Elliptical section with quadrupoles
  - – Change FDF to FD structure, rematch is easer, but need dual polarity current supply for magnet

4. Compensation–rematch of major element failures

1. Initial operation

Injector

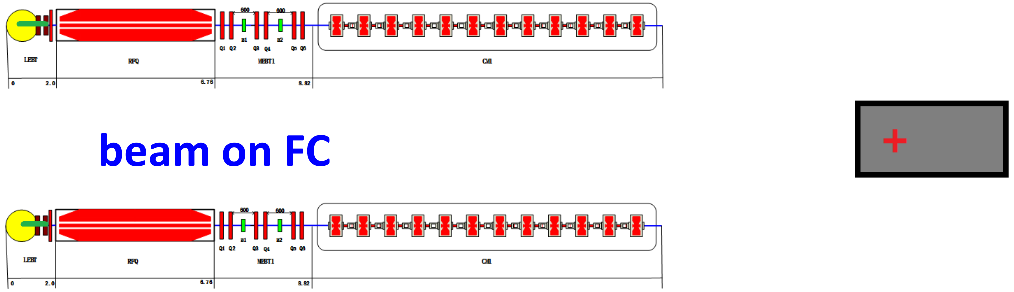
Operational injector 1: RF + beam ON



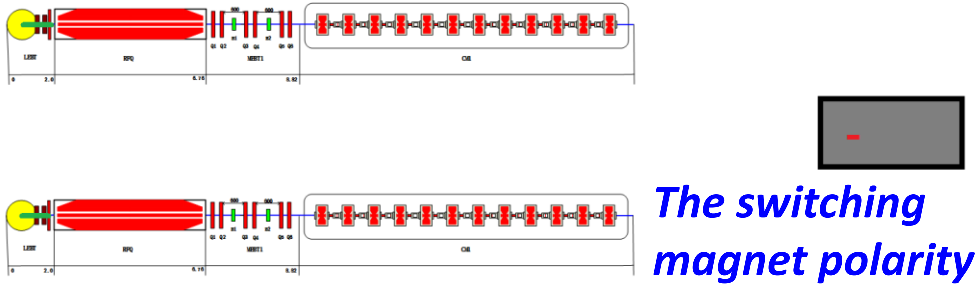
Warm stand by injector 2: RF on, beam on FC
Need check status frequently

2. A failure is detected anywhere

Beam stopped in injector 1 by MPS by Chopper



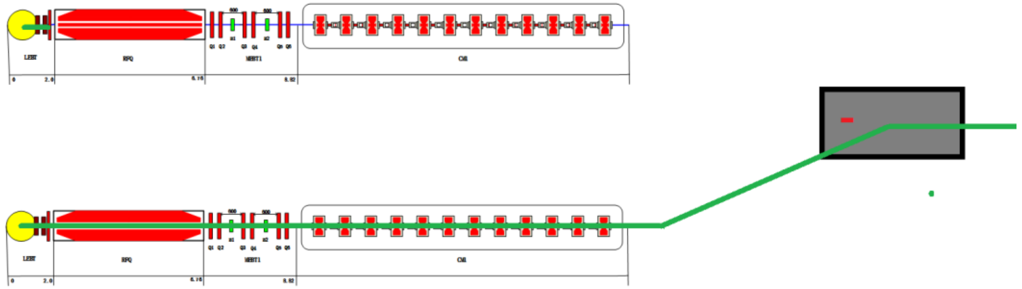
3. The failure is localized in injector and can not recover in few seconds (***diagnostic***)



The switching magnet polarity is changed (1~2 s)

4. Beam is recovered

Injector 1 to repaired or re-commissioning



Injector 2 operational with in 10 s

4. Compensation–rematch of major element failures

A failure is detected
Beam is stopped by the MPS by Chopper in injector

↓

The fault is localized, then diagnostic system determine the fault can recover in few seconds without any other change (A) or need compensation-rematch (B)

A:

Recover facilities

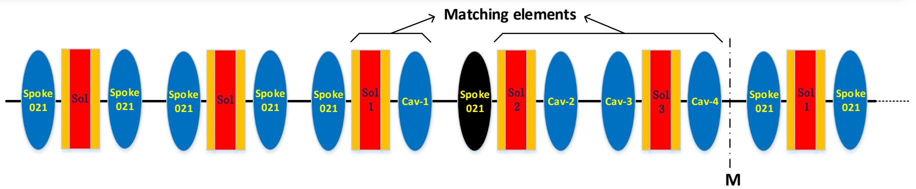
B:

The failed cavity is detuned (to avoid the beam loading effect) or magnet closed
Cold Tuning System

New V/φ setting-points are updated in cavities by compensation-rematch method
Two methods to discussion

Steady state

Beam recover (< 10 s)



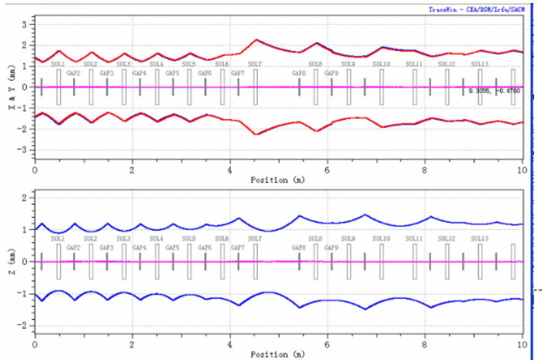
Example:
Spoke012: designed bandwidth is about 232 Hz, and measurements are within 10% range
If detuned 100*bandwidth~23 kHz, need tuning speed > 2.5 kHz/s, now < 1kHz/s

4. Compensation–rematch of major element failures

- There are two methods to get the compensation-rematch results
  - **Table lookup method**: Setting-points determined in advance, then save into database, if detected the failed index signal, find the right setting-points

    @ SHAO Yong
    - Simple, stabilization, controllable
    - Need a lot of works in advance for simulation and database establishment (should avoid human error)
  - **Hardware compensation and rematch:** using FPGA to calculated online

    @ XUE Zhou
    - Arithmetic computing speed is higher, as an integrated circuit device consisting of logic gates, an FPGA is able to realize parallel calculating and synchronous processing.
    - Instantaneous compensation and rematch is easier. It is an easier way to connect with the low level RF system and other types of hardware facilities etc.
    - Good portability and repeatability, no need a lot of calculation in advance.
    - Errors between models in FPGA and dynamic simulation
    - Uncontrollable, need more consideration and judge on the results

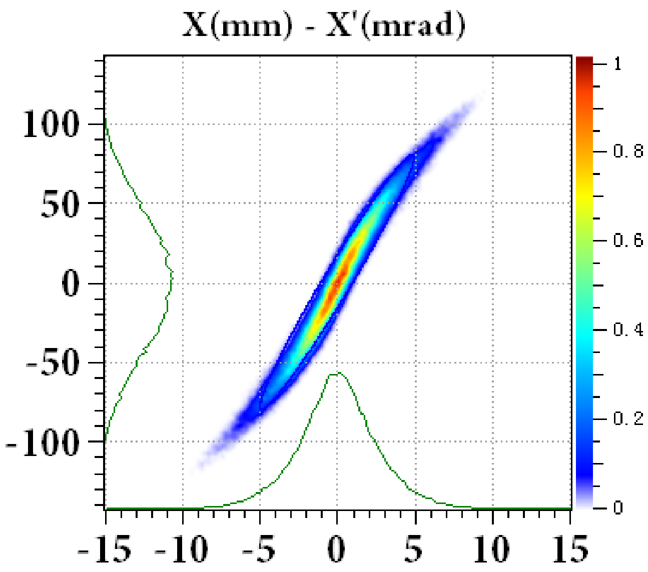


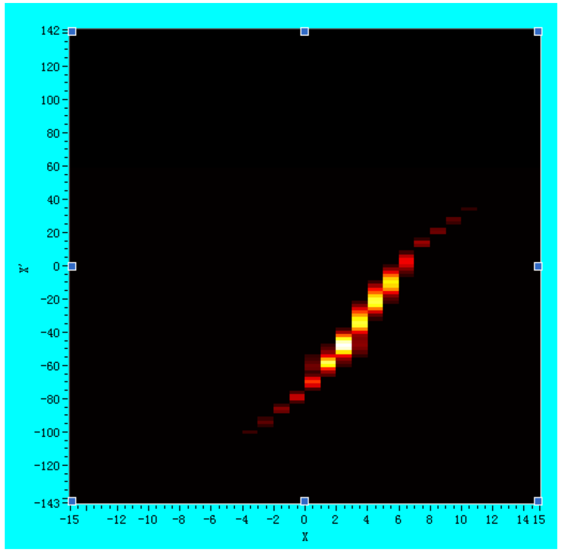
Take injector-I as an example:
It takes 9.2s to find the best result under 20MHz with hardware method. However the system clock is 200MHz, it needs continuous optimization to reduce the whole time.

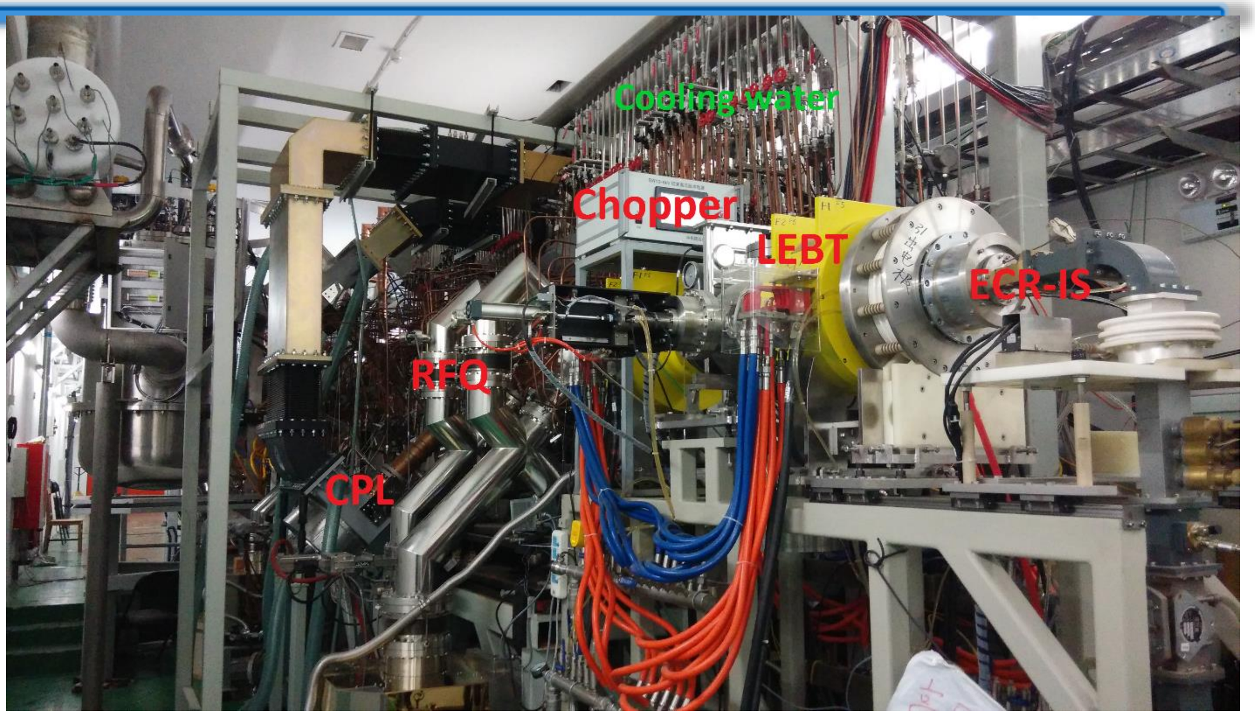
Twiss parameters	nominal	After compensation and rematch	Mismatch Factor
Beta-x	1.9548	1.9245	3.72%
Alpha-x	0.5476	0.4683	
Beta-y	1.9856	1.9687	3.94%
Alpha-y	0.5599	0.4787	
Beta-z	1.2822	1.3623	3.90%
Alpha-z	-0.3446	-0.3181	

5. Beam commissioning of CADS injector-I

- LEBT commissioning



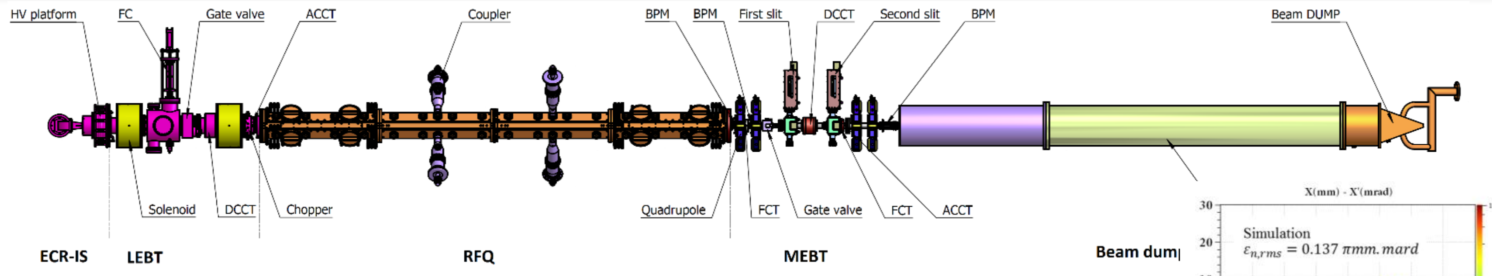


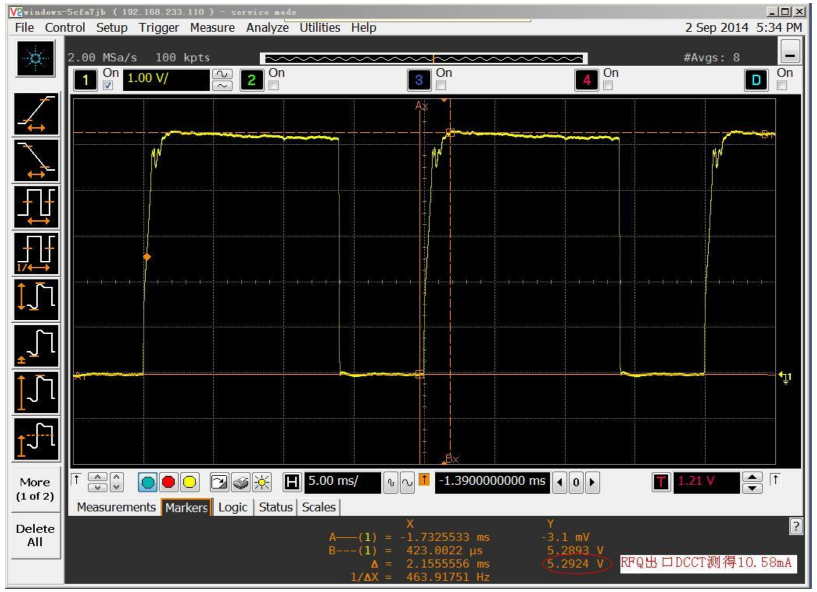


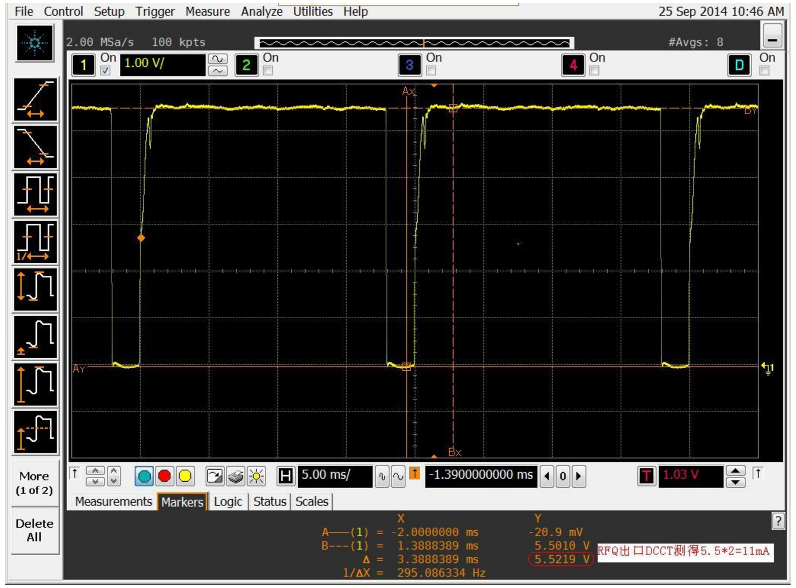
	Current	*α*	*β*	$\varepsilon_{n,r}$
	mA		mm/mrad	π mm.mrad
RFQ entrance matched beam	10	2.41	0.0771	≤ 0.2
Measured beam	11.5	2.18	0.0774	0.14

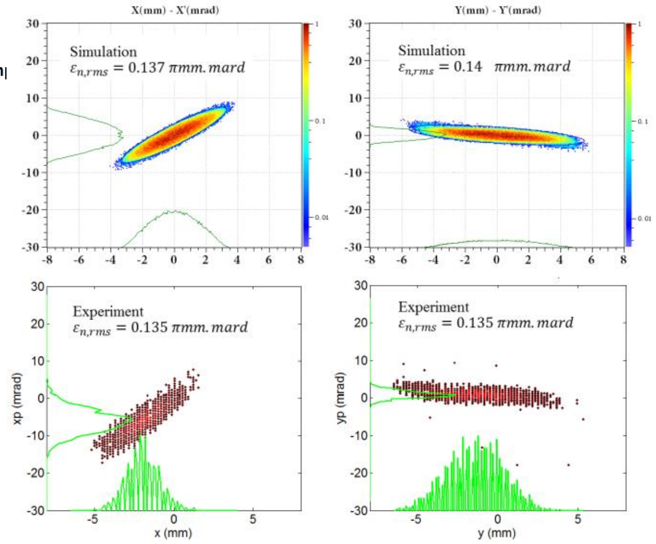
5. Beam commissioning of CADS injector-I

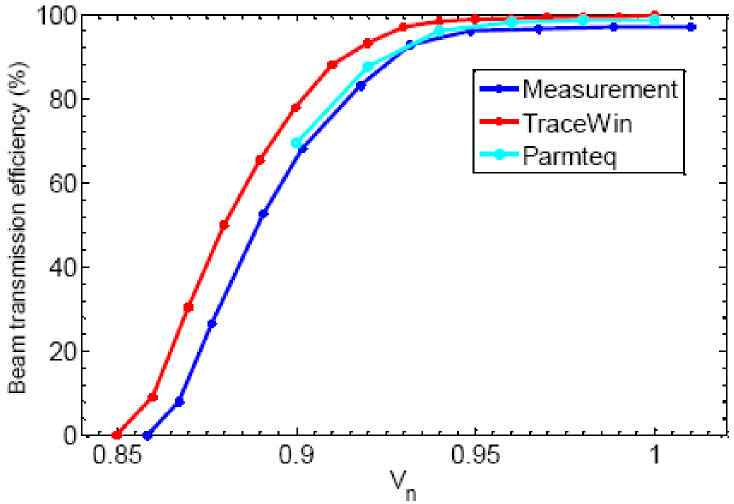
- RFQ commissioning
  - 325 MHz











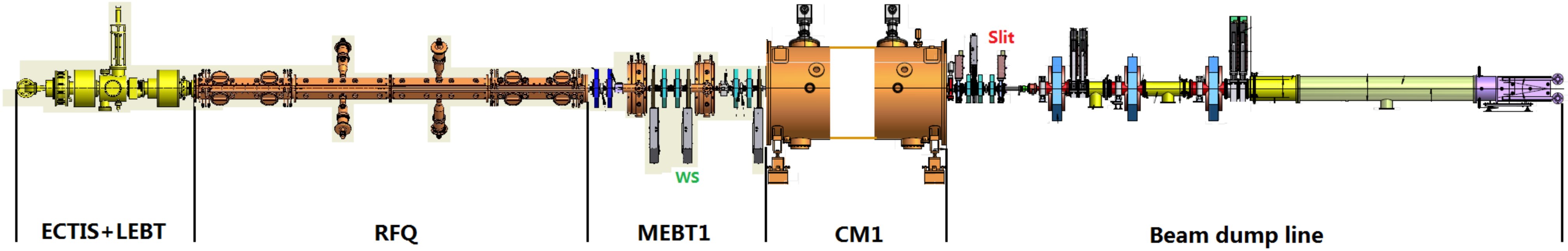
Beam duty factor: 70%
Beam transmission efficiency: 95%
Beam current@RFQ exit: 10.6 mA

Beam duty factor: 90%
Beam transmission efficiency: 90%
Beam current@RFQ exit: 11.0 mA

31 kW

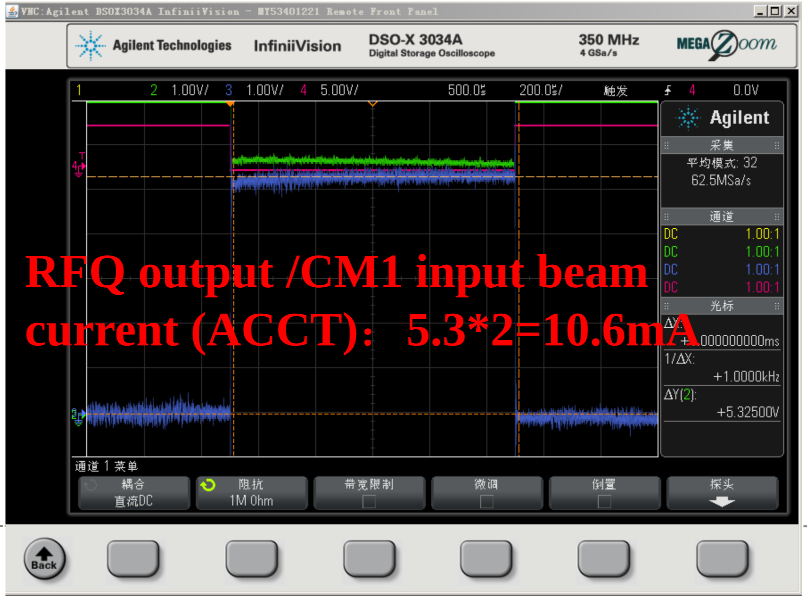
5. Beam commissioning of CADS injector-I

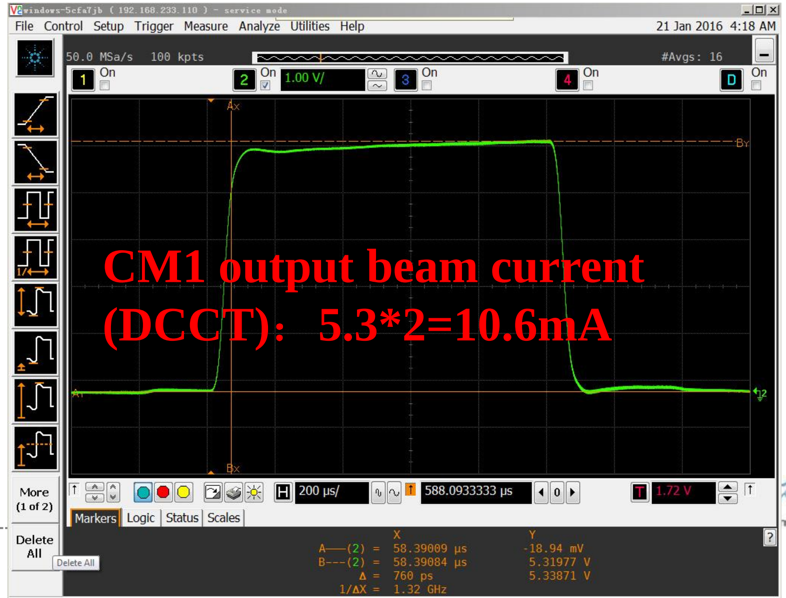
- CM1 commissioning
  - ECRIS+LEBT+RFQ+MEBT1+CM1 (7 spoke012/7 cold BPM/ 7 solenoid)+Beam dump line



Beam duty factor: 2‰ (2Hz/1ms)

- **CM 1 output energy with 7 cavities : Eout=6MeV**
- **CM1 transmission: 100%**
- **RFQ+CM1 transmission: 88.4%**
- **Output current: 10.6mA**

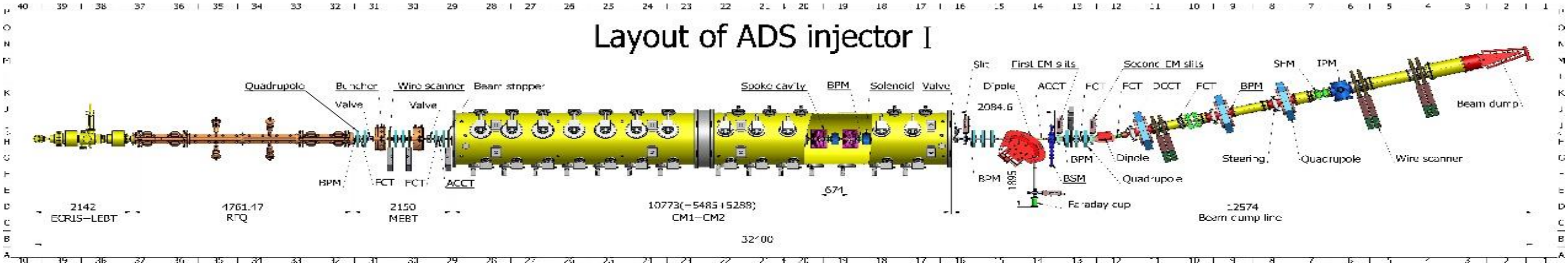


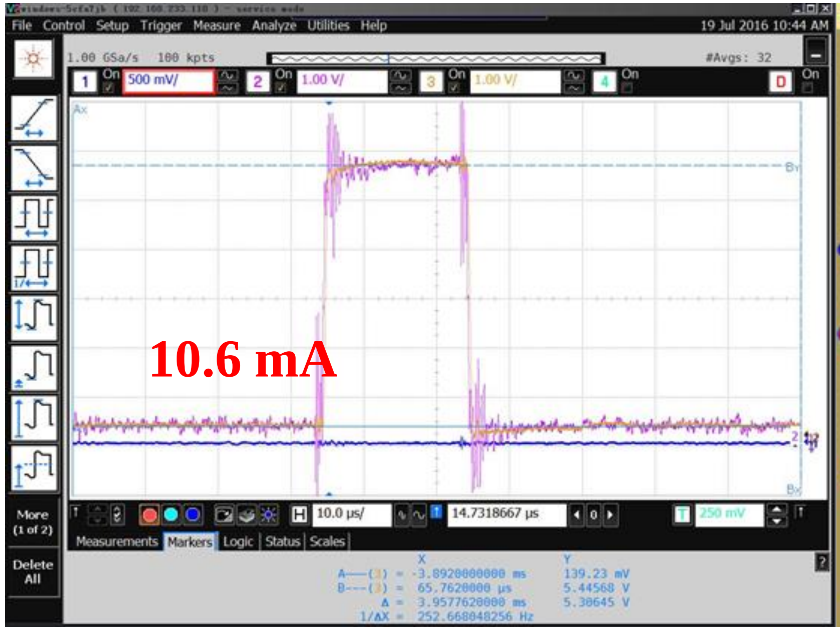


5. Beam commissioning of CADS injector-I

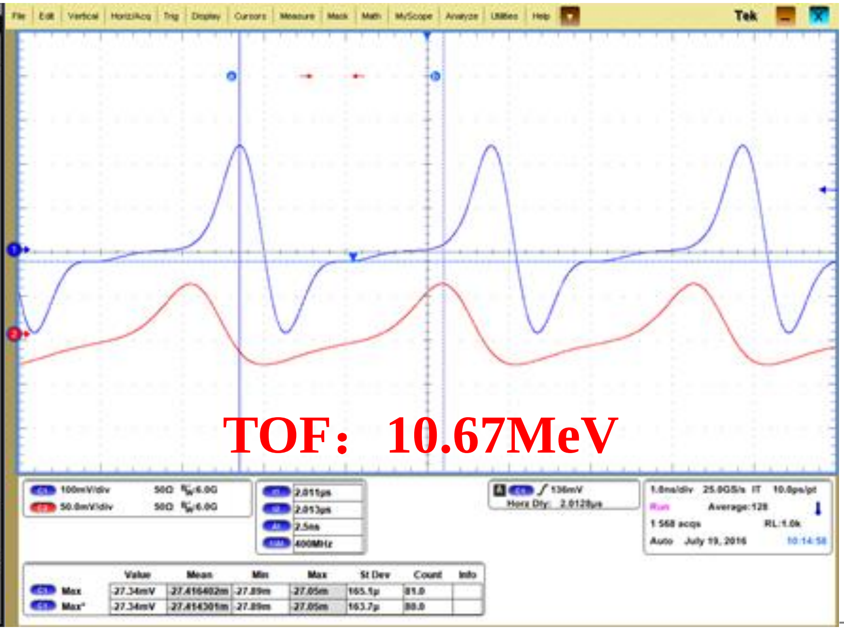
ECRIS+LEBT+RFQ+MEBT1+CM1+CM2+Beam dump line

5Hz/20 us

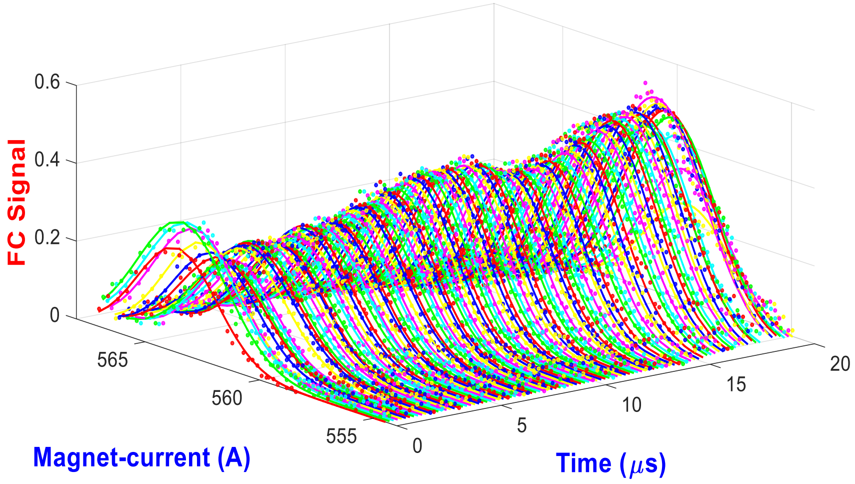




10.6 mA



TOF: 10.67MeV



Bunch rms energy spread: 0.32%

6. Summary

- CADS accelerator lattice have been presented with serious design
- Beam loss control have been discussed, including errors analysis and mismatch study
- Accelerator reliability have been discussed: study the compensation–rematch method of major element failures; give a preliminary processing of compensation; present table lookup method and hardware compensation and rematch method;
- Beam commissioning of CADS injector-I have been proposed, the RFQ duty factor with beam reached 90%. Very short beam have been commissioned to 10.67 MeV@ 10.6 mA.