Development and Application of High-Performance CISP-GPU Code for High Intensity Effects in HIAF

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Outlines

1. Introduction

2. Development of CISP-GPU

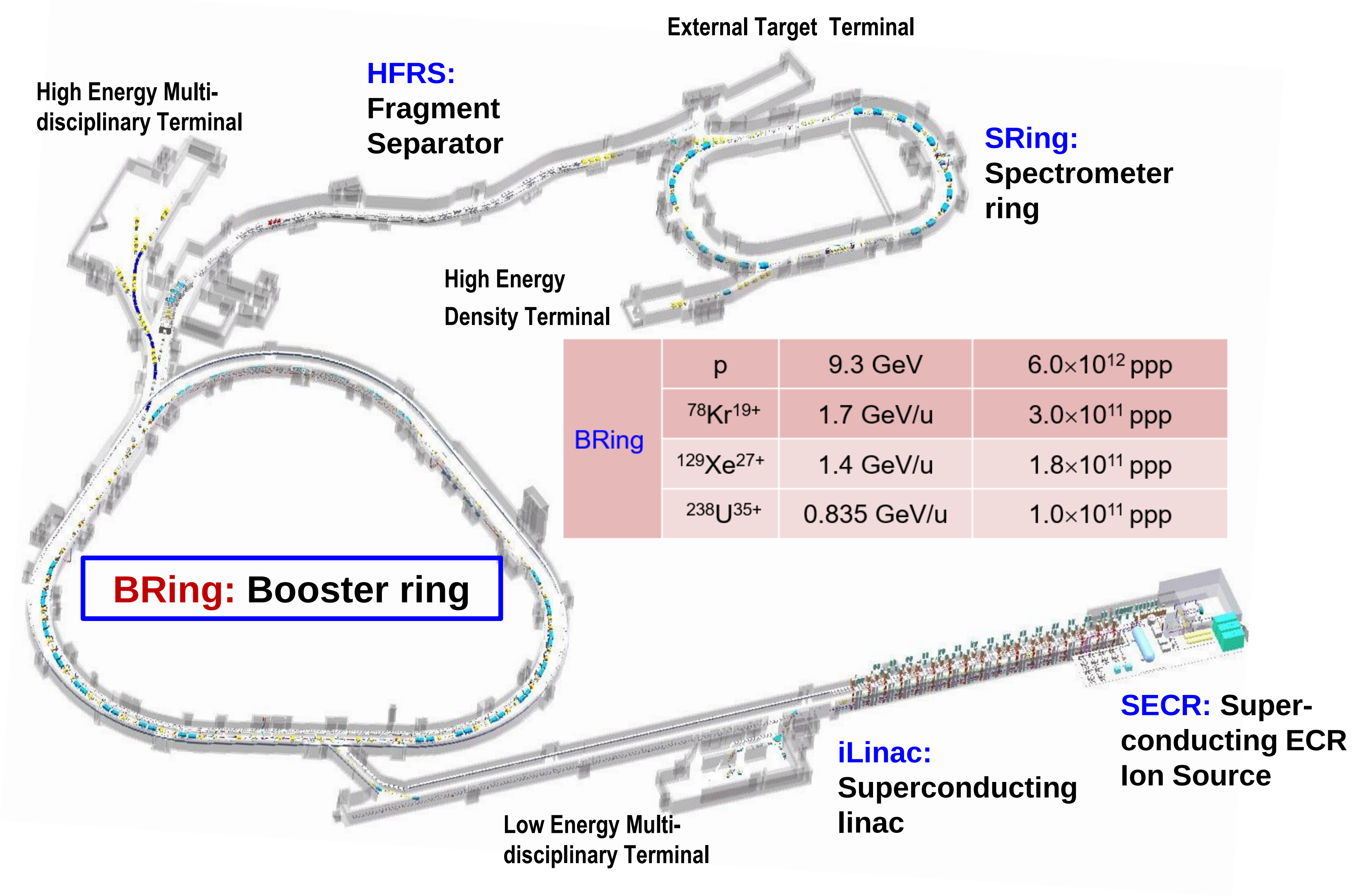
3. Nonlinear and Space Charge Effects

4. Collective Instabilities

5. Conclusions and Discussions

1. Introduction

➢ **High Intensity heavy-ion Accelerator Facility (HIAF)**



BRing	p	9.3 GeV	6.0×10^{12} ppp
	$^{78}Kr^{19+}$	1.7 GeV/u	3.0×10^{11} ppp
	$^{129}Xe^{27+}$	1.4 GeV/u	1.8×10^{11} ppp
	$^{238}U^{35+}$	0.835 GeV/u	1.0×10^{11} ppp

High intensity

- **Nonlinear effects**
- **Space charge effects**
- **Collective instabilities**

⬇ **Limit**

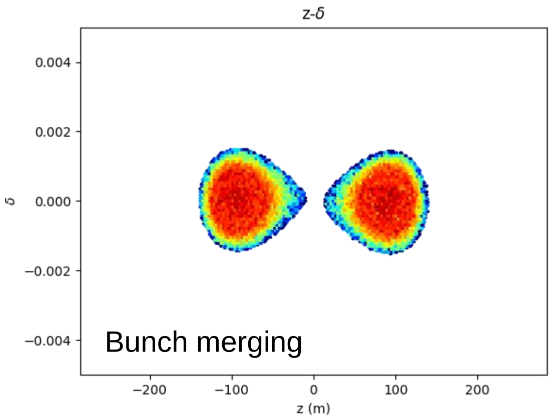
- **Beam intensity**
- **Beam quality**

☐ It is important to fully study **high intensity effects in the HIAF/BRing.**

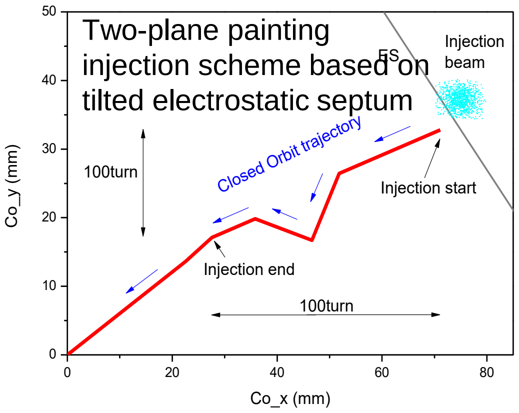
1. Introduction

- Many **complicated beam manipulations**, **entirely new dynamics schemes**, and **innovative technologies and designs** will be applied in the HIAF/BRing.

Innovations



Complicated manipulations



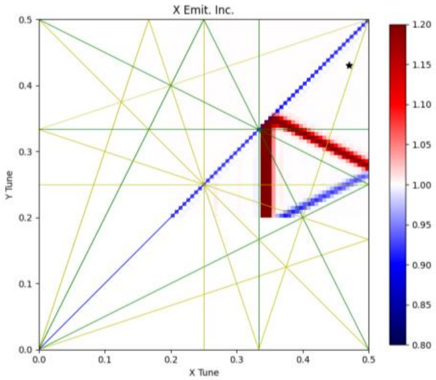
New dynamics schemes

New technologies and designs

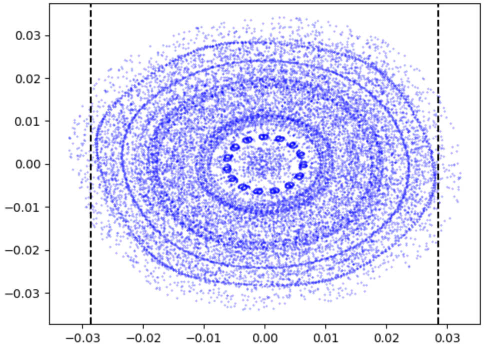
Properties

	Particle	Energy Range
BRing	p	48 ~ 9300 MeV
	$^{78}Kr^{19+}$	27 ~ 1700 MeV/u
	$^{238}U^{35+}$	17 ~ 835 MeV/u

Wide energy ranges



Strong space charge fields



Severe nonlinear effects

The coupling effects of those complicated dynamics and high intensity effects must be **evaluated by highly accurate simulations closer to real situations**.

Powerful tools needed urgently!

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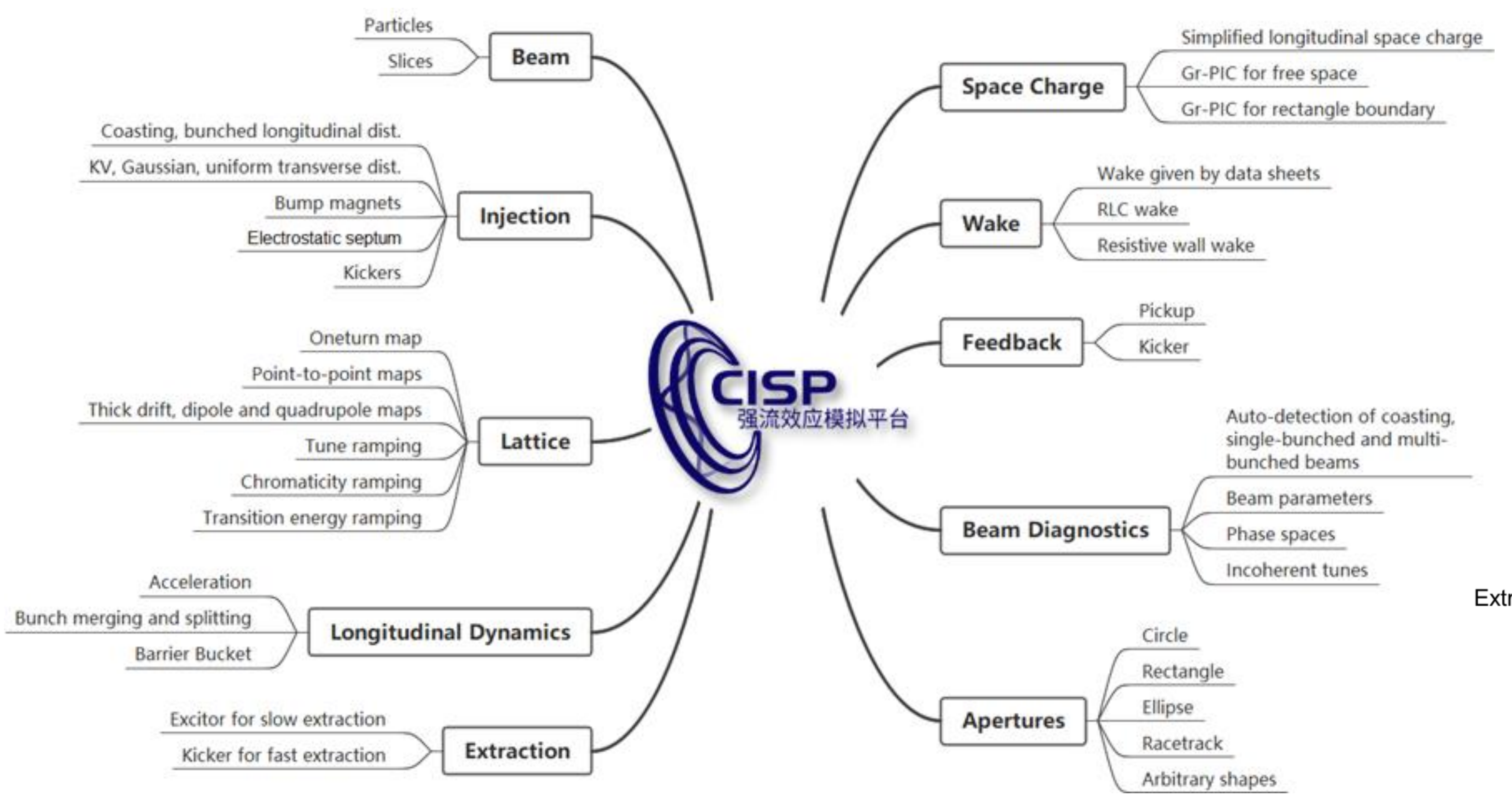
2. Development of CISP-GPU

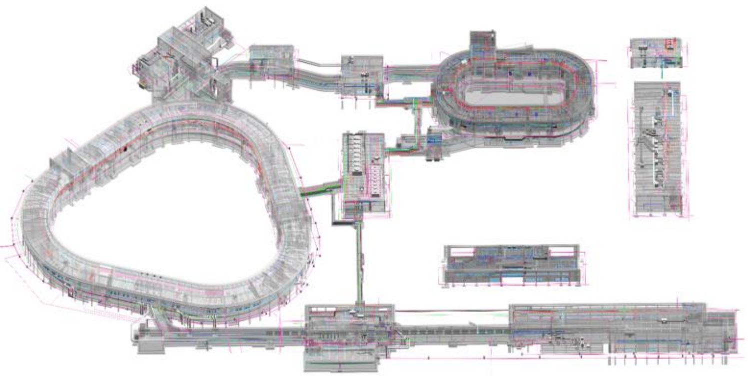
An advanced software platform CISP and its GPU version are developed to simulate high intensity effects and their coupling effects in all manipulations

CISP 强流效应模拟平台

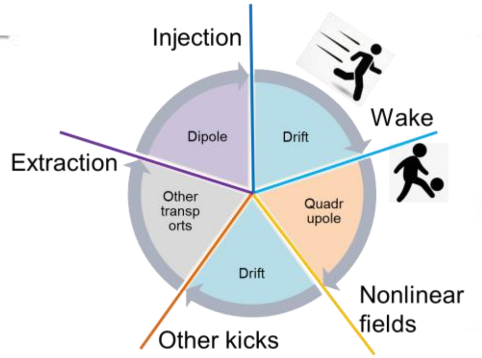
https://cisp.accsoftware.cn

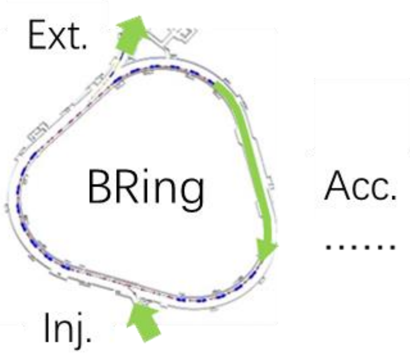
Simulation Platform for Collective Instabilities



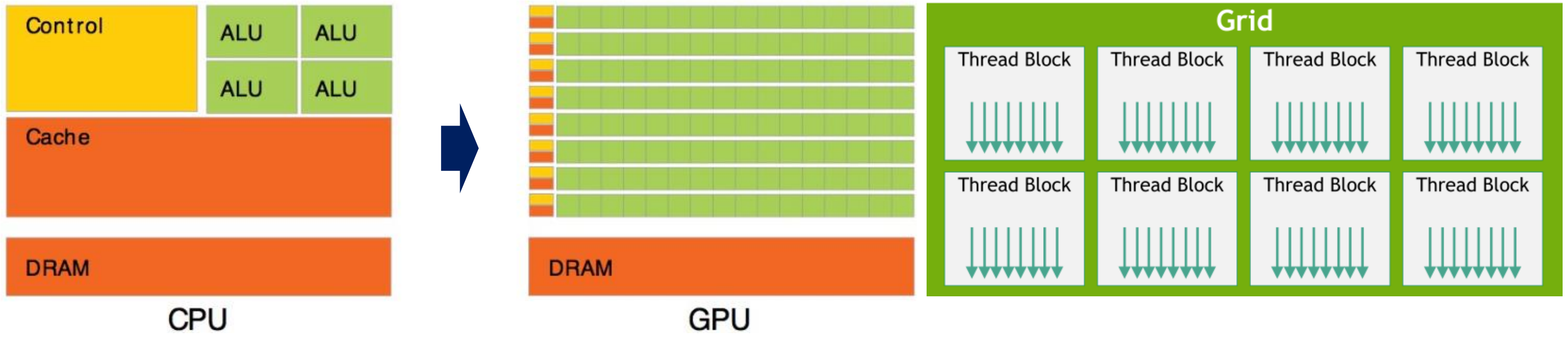


1:1 end-to-end!



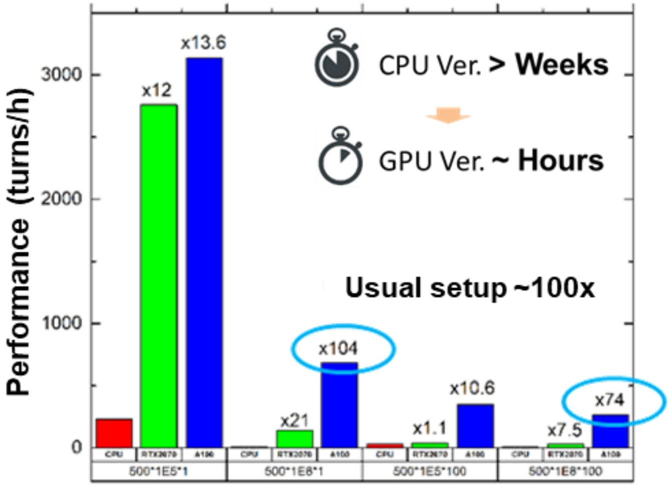


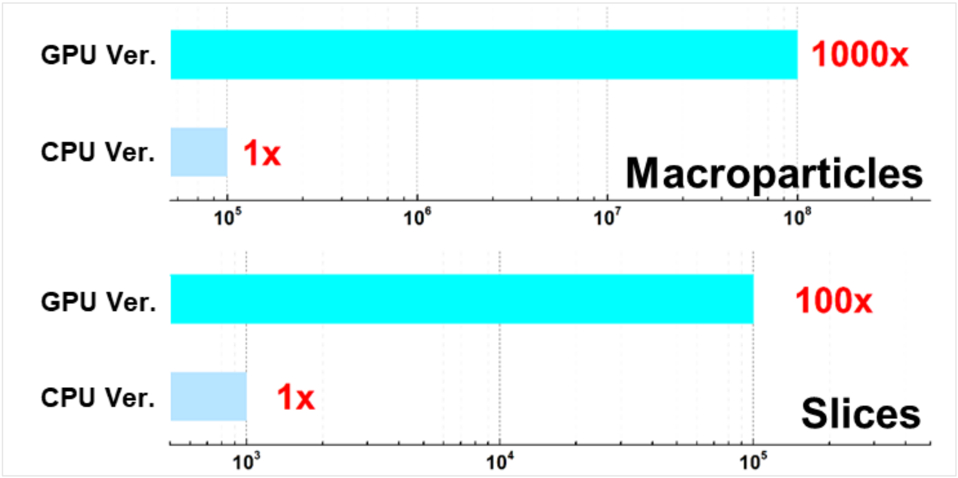
2. Development of CISP-GPU



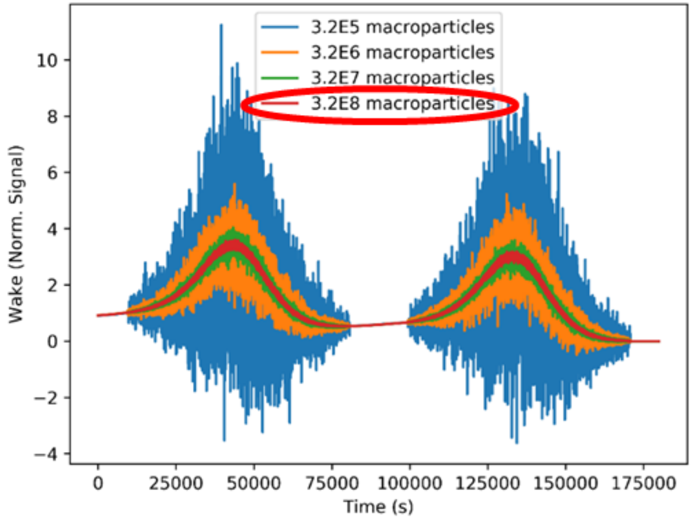
- **All beam dynamics simulations are performed in the GPUs** to **get much higher performance**

High performance





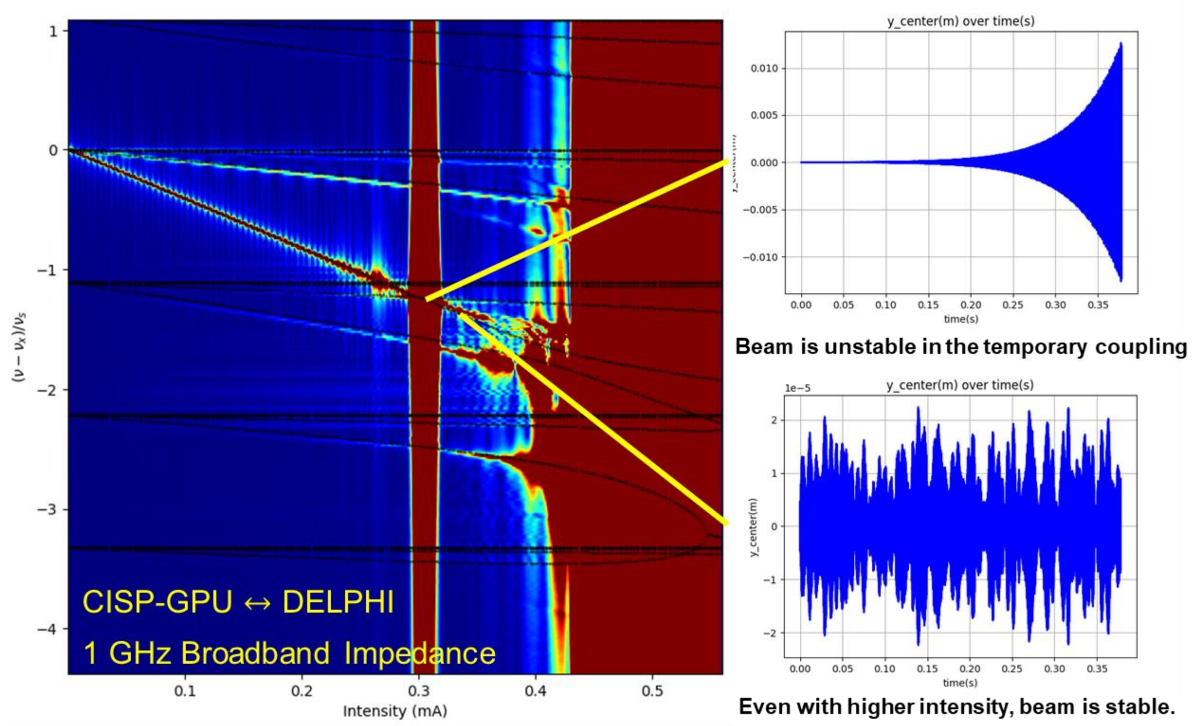
Low noise and high accuracy



- Maximal capability of CISP-GPU (1 GPU) ~ **10^8 macroparticles, 10^5 beam slices for wake simulations**
- Study the interaction between **ultra-short wakes and ultra-long bunches or dynamics like this situation**, as well as **many other coupling dynamics of high intensity effects** in ion accelerators

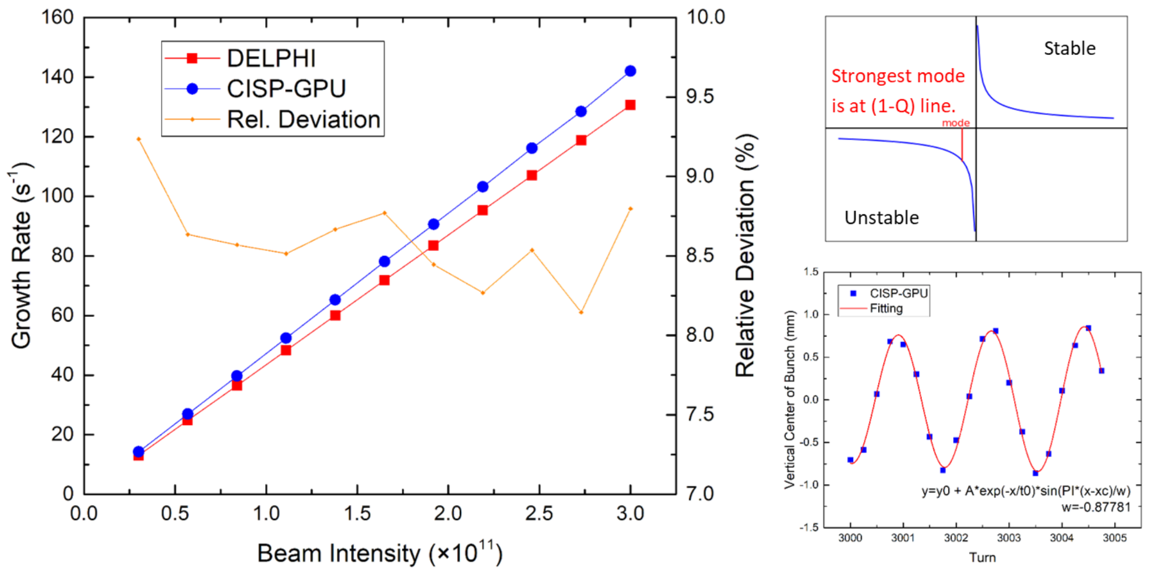
2. Development of CISP-GPU – Wakes

➢ **Transverse mode coupling instability in the SPS, CERN**



- The **mode shifts, the coupling and decoupling of modes, and whether the beam is stable at a specific intensity** are similar in the CISP-GPU and the DELPHI* results

➢ **Transverse coupled bunch instability: CISP-GPU ↔ DELPHI & Theory**

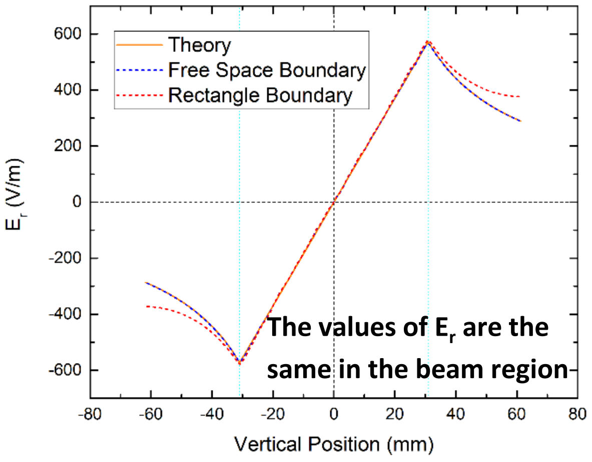


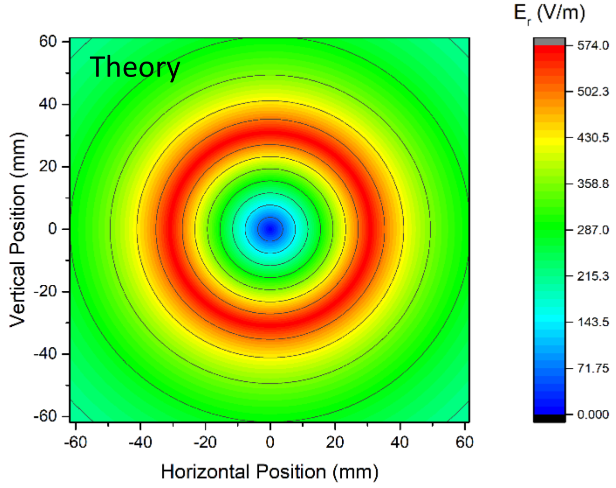
- **The growth rates given by the CISP-GPU are proportional to the beam intensities**, and the deviation of slopes from DELPHI is less than 10%.
- The phase advance of adjacent bunches is **0.285π** in the simulations, indicating **(1-Q) line**.

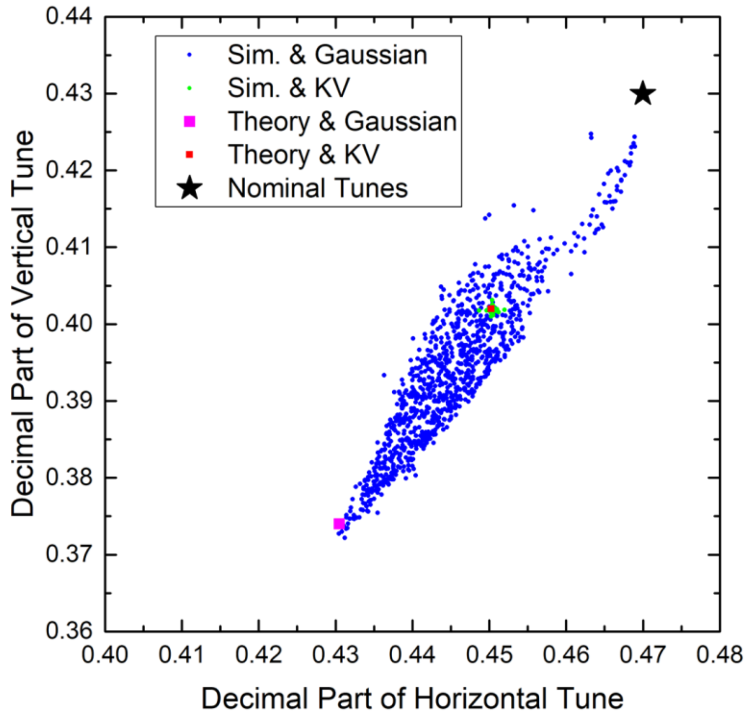
*DELPHI (Discrete Expansion over Laguerre Polynomials and Headtall modes), N.Mounet, N.Biancacci, D.Amorim, CERN

2. Development of CISP-GPU – Space Charge

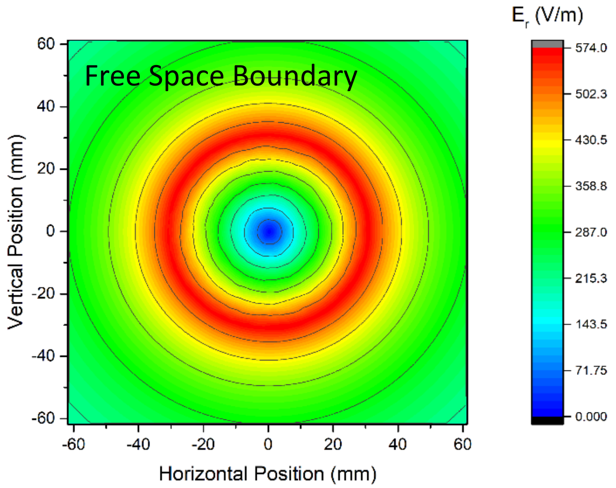
➢ **Space charge fields and tune spreads: CISP-GPU ↔ Theory**

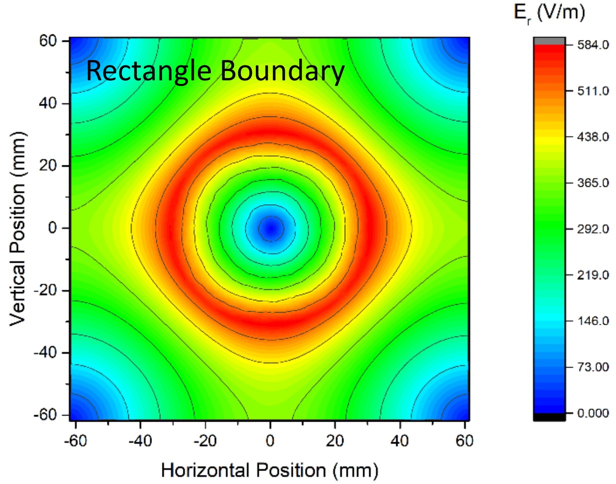






The values and shapes of space charge fields from CISP-GPU and theory agree with each other!

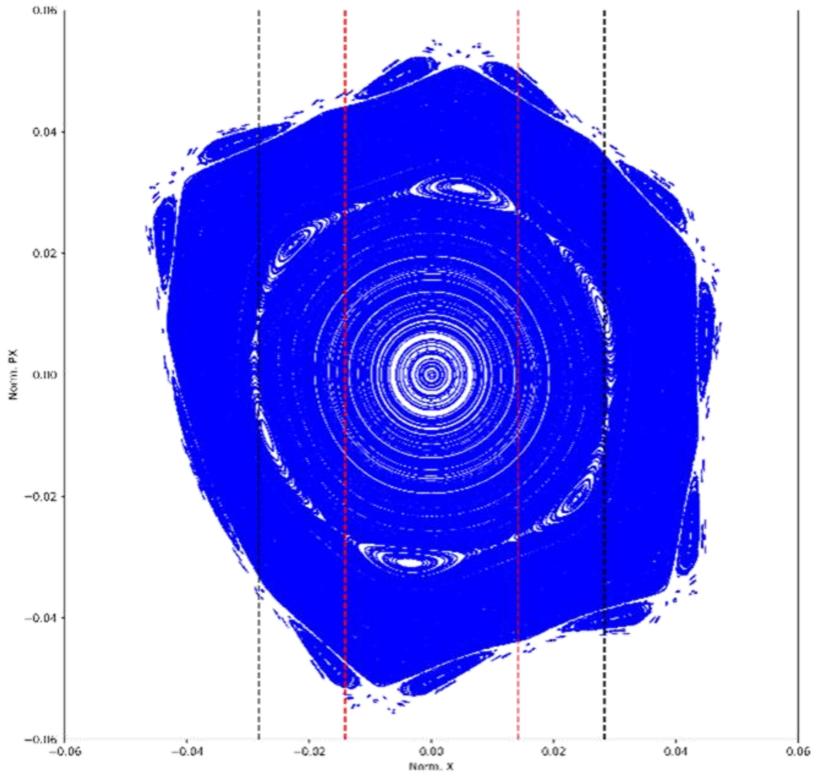




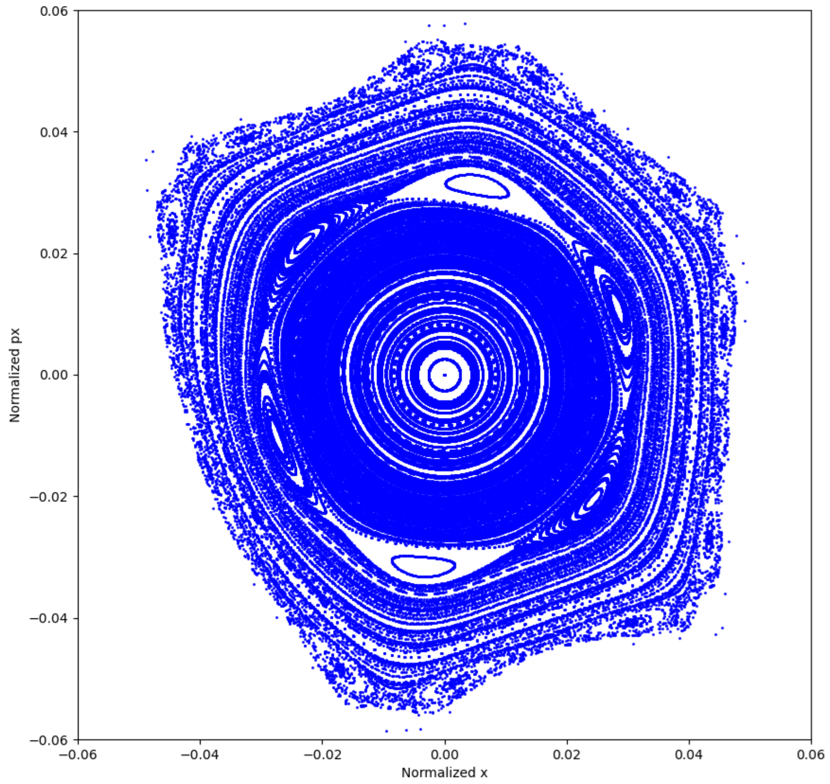
The tune spreads of various distributions are almost the same from the CISP-GPU and the theory.

2. Development of CISP-GPU – Nonlinear Fields

➢ **Phase spaces with sextupole magnets: CISP-GPU ↔ MADX PTC***



CISP-GPU



MADX PTC

The phase spaces given by CISP-GPU and MADX PTC are almost the same, and similar stable islands are identified from inside to outside in two methods.

CISP-GPU is ready for the studies of beam dynamics in the HIAF/BRing!

*MAD - Methodical Accelerator Design, BE/ABP Accelerator Beam Physics Group, CERN

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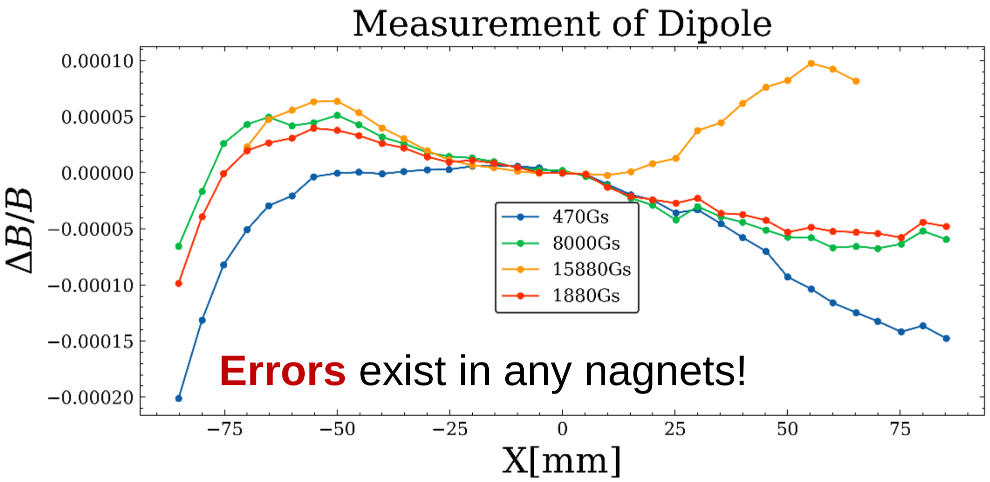
3. Nonlinear and Space Charge Effects

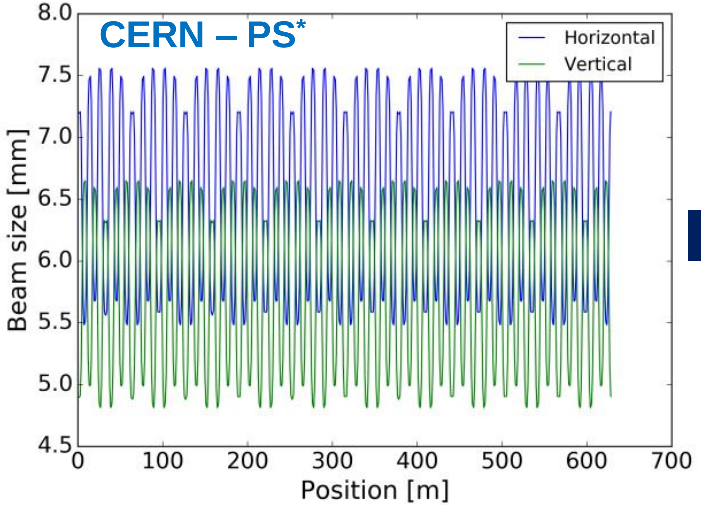
➢ **Concentrating on incoherent effects**

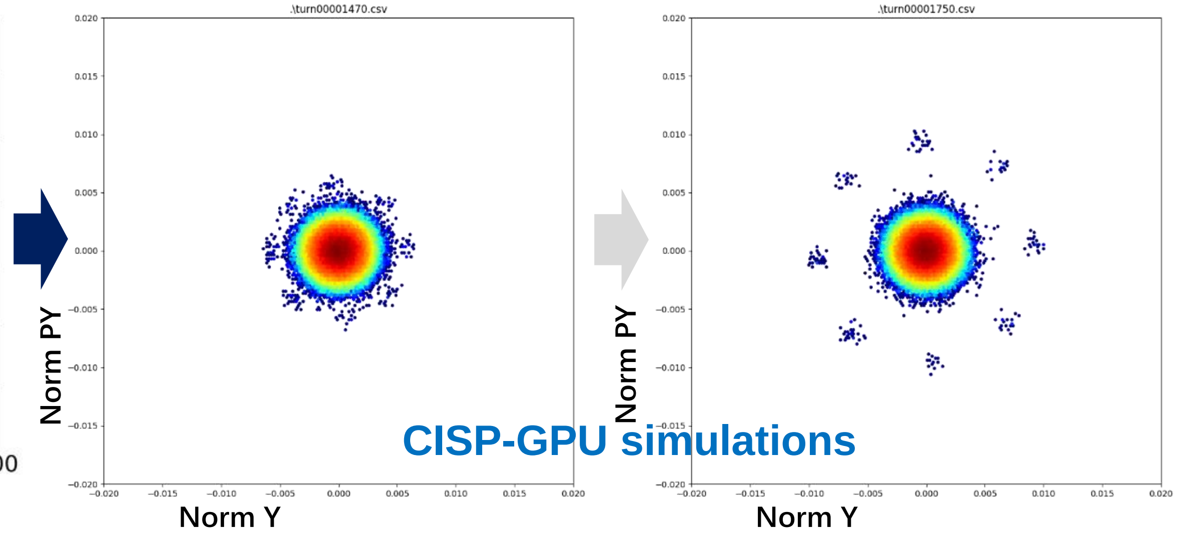
1. Resonances driven by magnet errors – compensation schemes should be designed

Two Key Effects

2. Structural resonances – Space charge fields interacts with periodic lattice structure





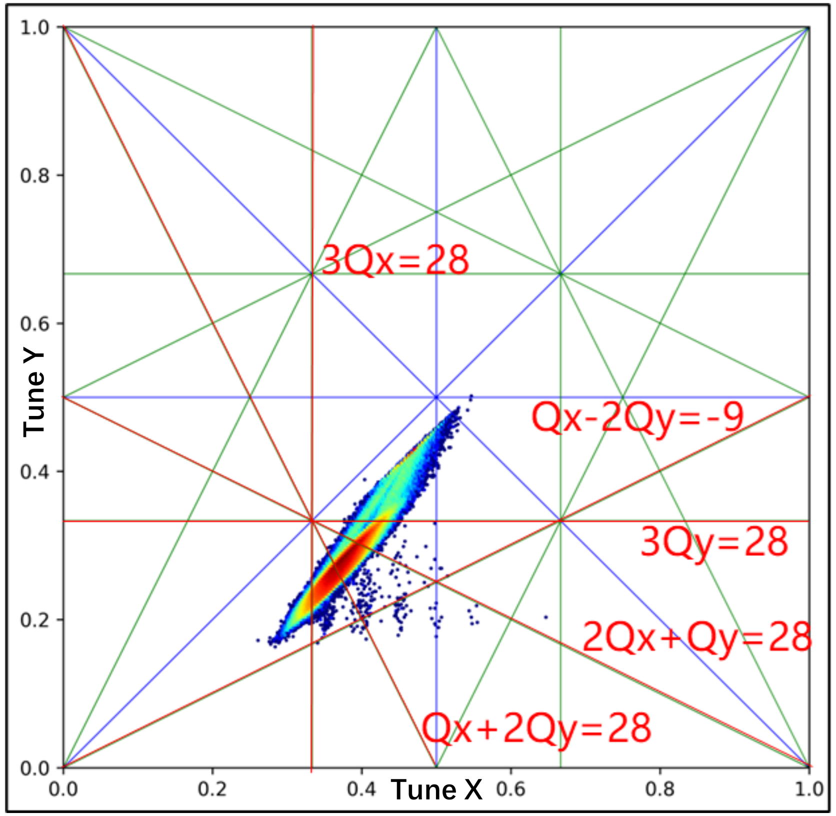


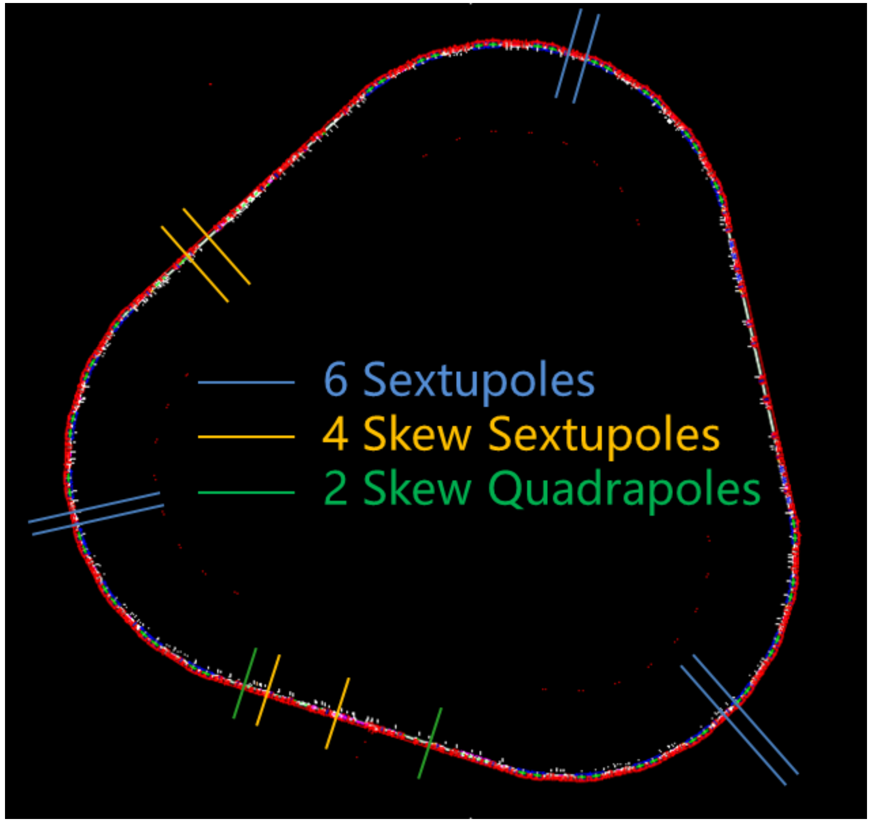
➢ Coherent effects of space charge fields still wait for further studies.

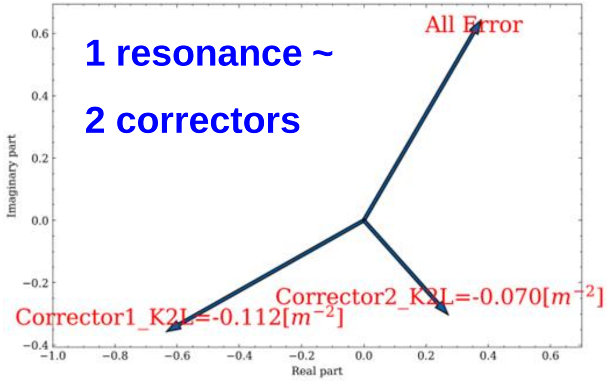
*Space charge and lattice driven resonances at the CERN injectors, Foteini Asvesta, PhD Thesis, CERN and National Technical University of Athens, 2020

3. Nonlinear and Space Charge Effects – Field Errors

- Investigate 3rd order resonances stimulated by sextupole errors







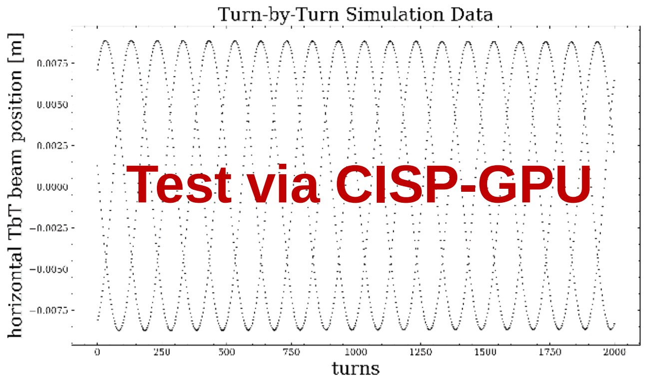
6 normal sextupole magnets and 4 skew sextupole magnets are needed to compensate **3 normal sextupole and 2 skew sextupole driven resonances**.

Theory*: $\tilde{H}_w^{(n)} = \sum_{jklm}^{n=j+k+l+m} h_{w,jklm}(2J_x)^{\frac{j+k}{2}}(2J_y)^{\frac{l+m}{2}} e^{i[(j-k)(\phi_x+\phi_{x,0})+(l-m)(\phi_y+\phi_{y,0})]}$

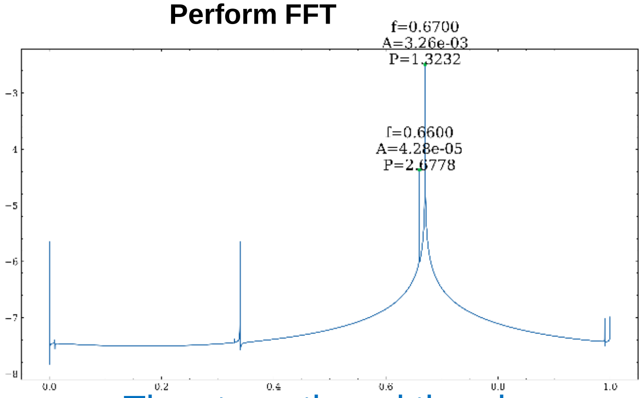
*Studies and Measurements of Linear Coupling and Nonlinearities in Hadron Circular Accelerators, Andrea Franchi, Thesis: PhD Universität Frankfurt/M. (2006)

3. Nonlinear and Space Charge Effects – Field Errors

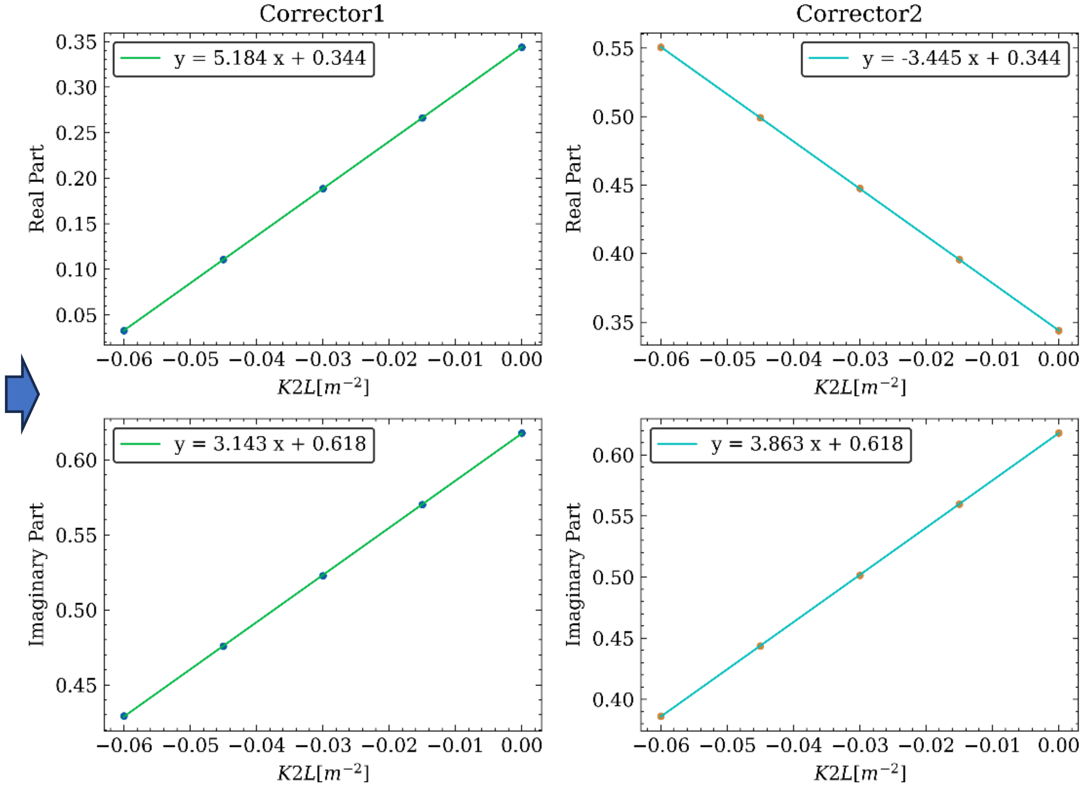
- If **considering zero intensity situation**, **the total sextupole error strength and direction could be measured by BPMs**, **and compensation scheme could be calculated directly**.



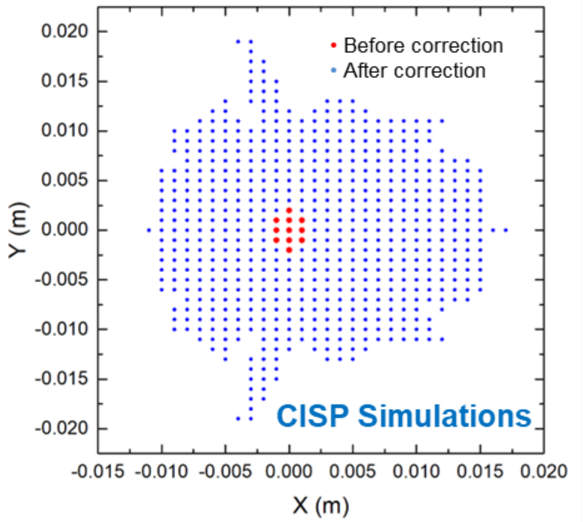
Perform FFT

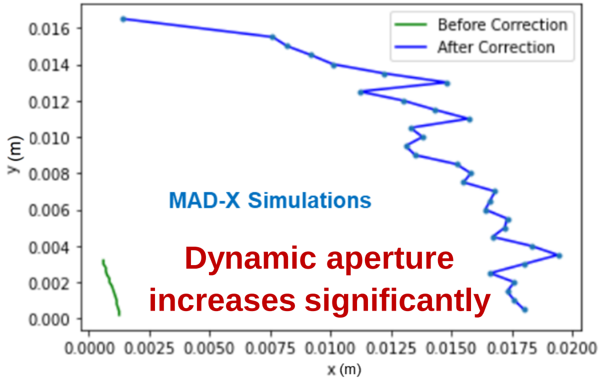


The strength and the phase of resonances is extracted



The effects of correctors to the resonances are also generated by CISP-GPU simulations.



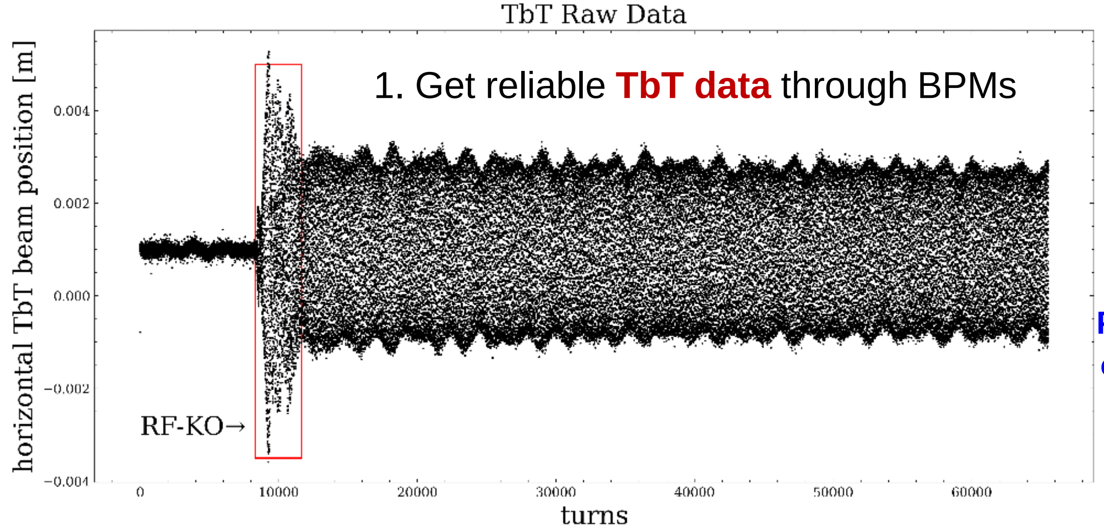


Simulations and theory calculations agree with each other very well, which makes it possible to conduct resonance compensation experiments.

Corrector1_K2L=-0.112[m^{-2}]
Corrector2_K2L=-0.070[m^{-2}]

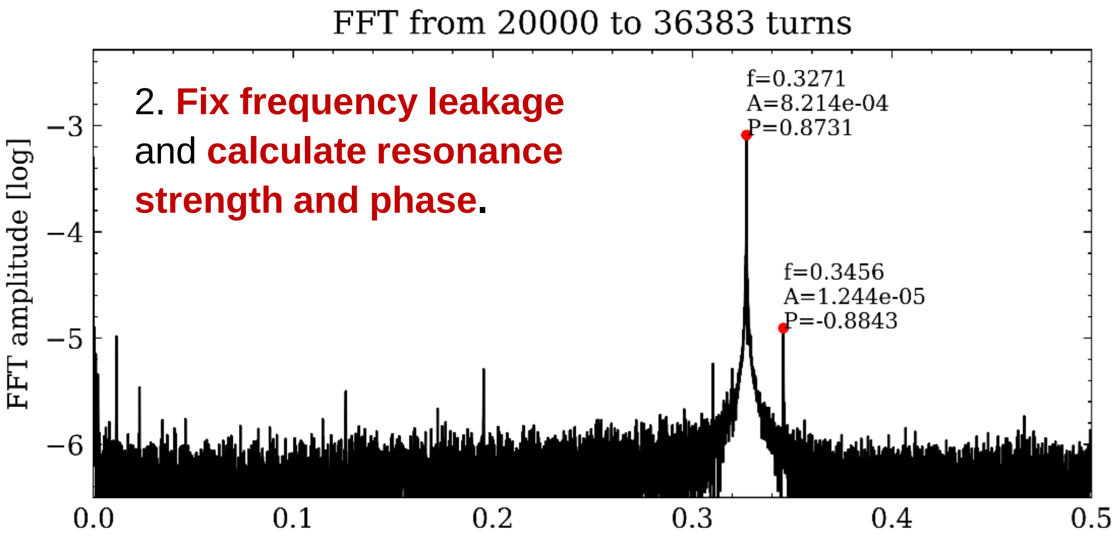
3. Nonlinear and Space Charge Effects – Field Errors

- A zero-intensity experiment is conducted on the Space Environment Simulation and Research Infrastructure, **SESRI, to compensate $3Q_x = N$ resonance with two sextupole correctors.**

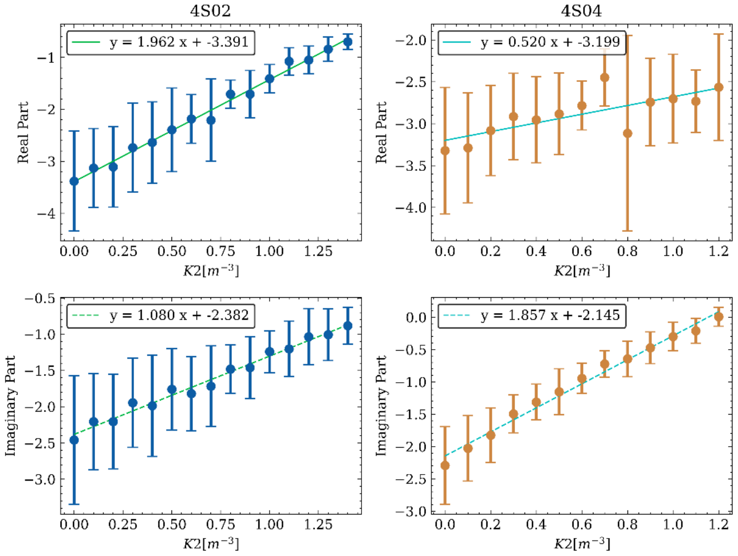


1. Get reliable **TbT data** through BPMs

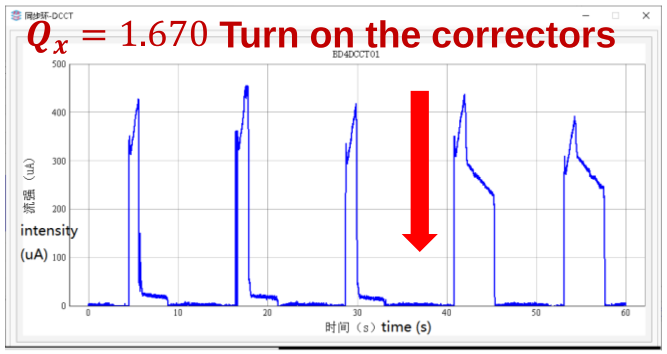
Perform FFT on TbT data

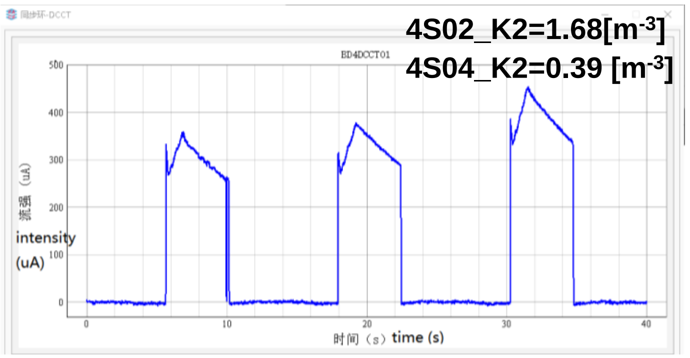


2. **Fix frequency leakage** and **calculate resonance strength and phase**.



3. Adjust correctors' strength to **measure the required linear relationships** in following compensation.





4. **Calculate and apply compensation**, the beam loss reduces shown by DCCT

The best compensation achieved at $Q_x = 1.670$.

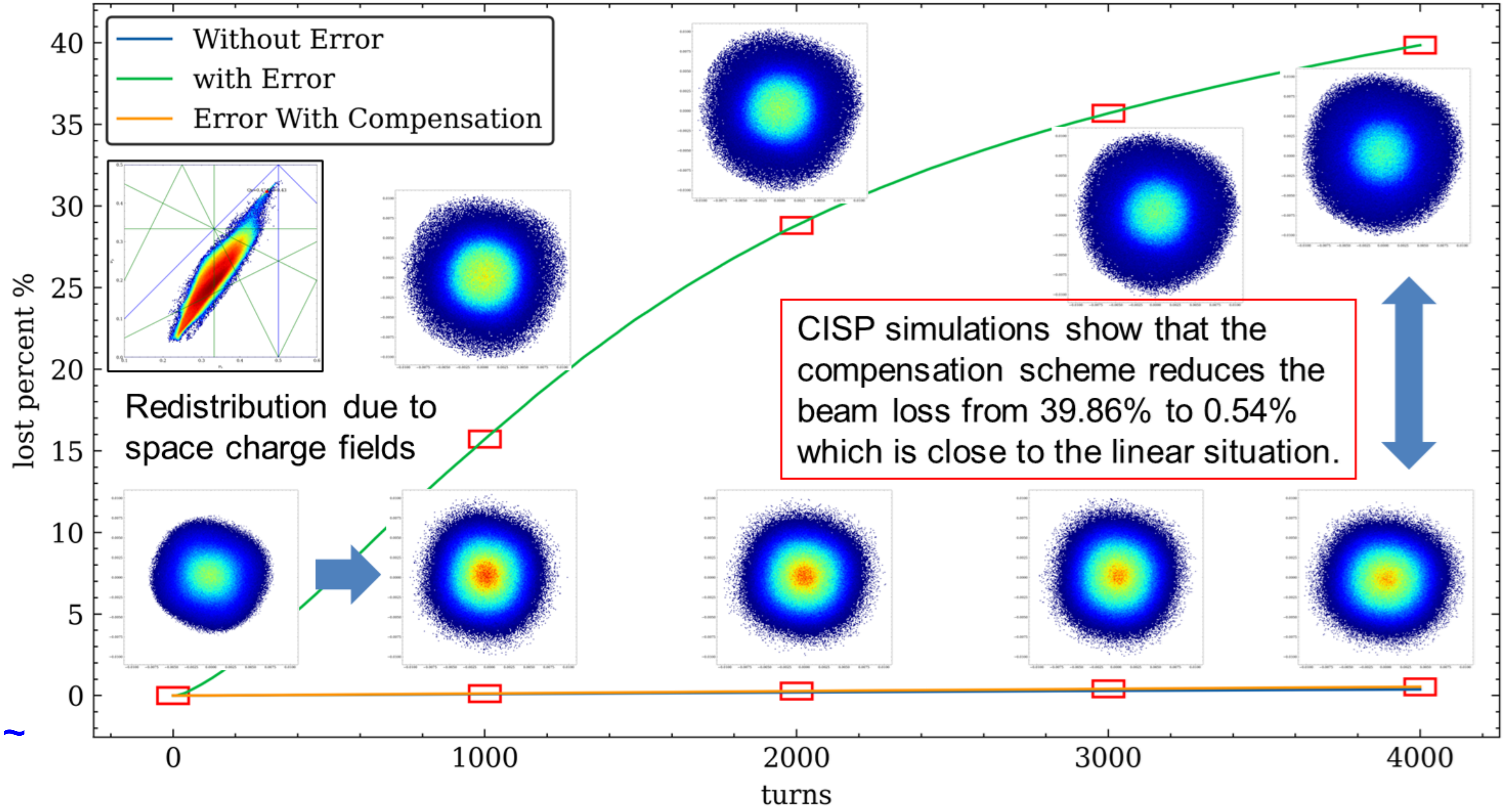
3. Nonlinear and Space Charge Effects – Field Errors

- **When considering strong space charge fields (high intensity situation), the previous method is still work for third order resonances except that the phases and betatron functions at all sextupole errors and correctors are different from the zero-intensity situation(?)**

- **Approximation:**

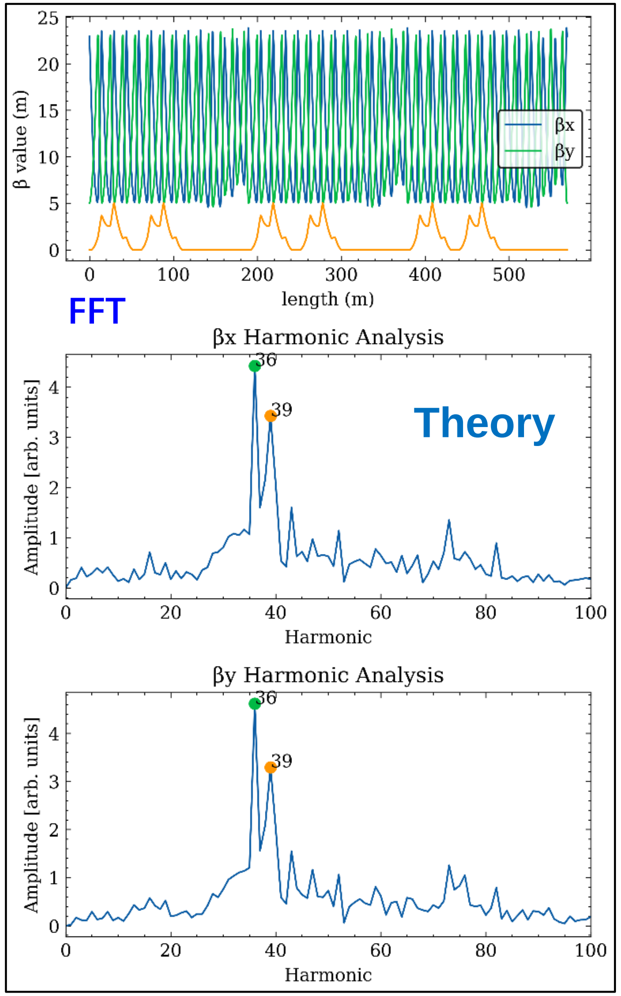
$$\beta_u \to \frac{\beta_u \nu_{0u}}{\nu_{0u} + \Delta\nu_u^{spch}}$$

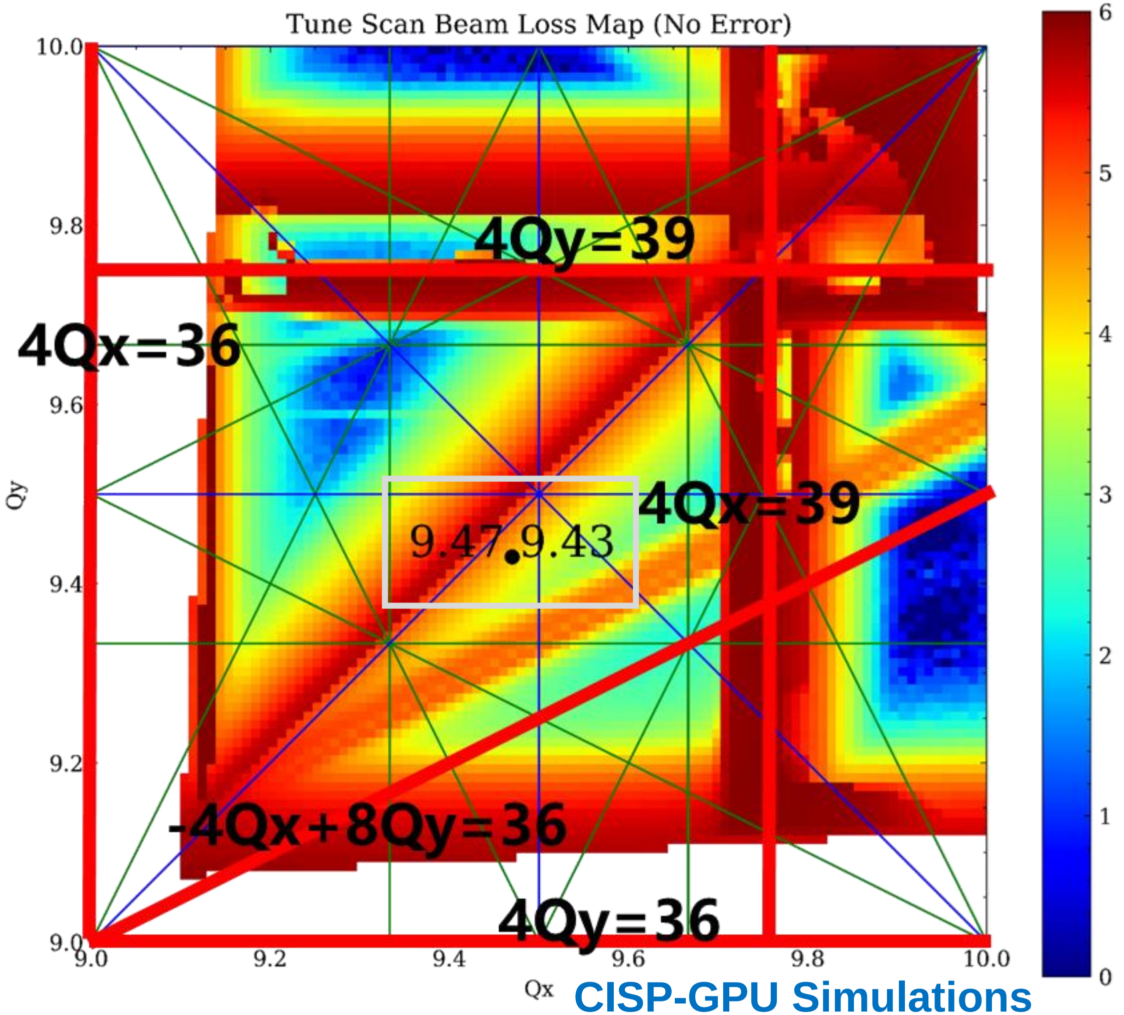
- It works when compensating 3rd order resonances in the CISP-GPU simulations



- **Still need more work ~**

- Theory indicates that **resonances of $mQ_x + nQ_y = 36\ or\ 39$ could be driven by space charge itself with periodic lattice in the HIAF/BRing**, which is verified by the CISP-GPU simulations.





CISP-GPU Simulations

- **Structural resonances $mQ_x + nQ_y = 36\ or\ 39$** are also identified in the CISP-GPU simulations.
- This research is helpful for choosing tunes in the future HIAF/BRing beam commissioning.
- But new compensation schemes are still under development now.

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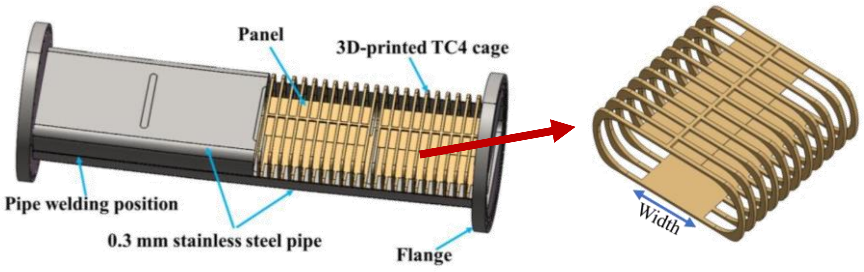
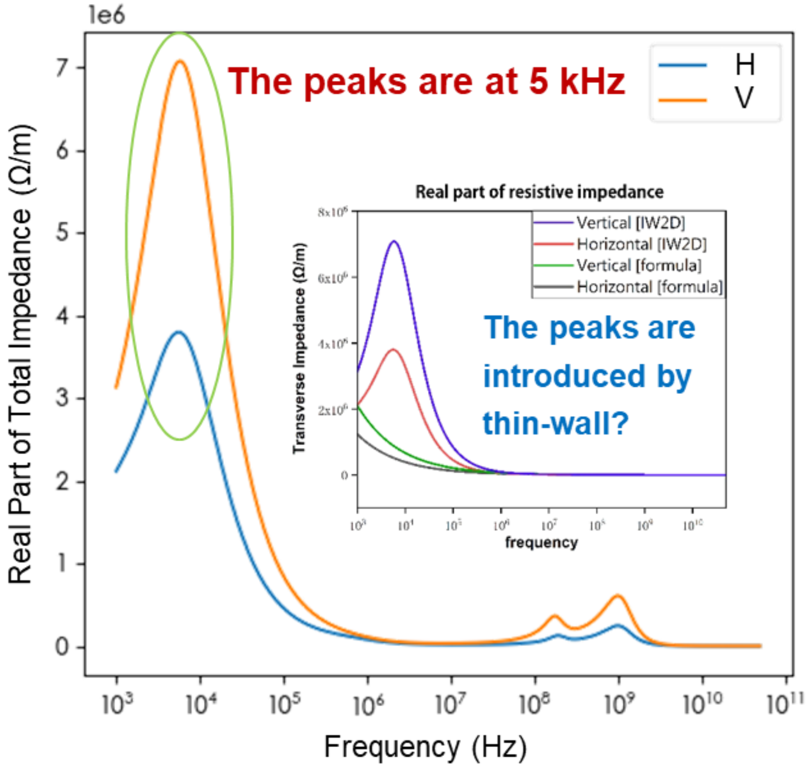
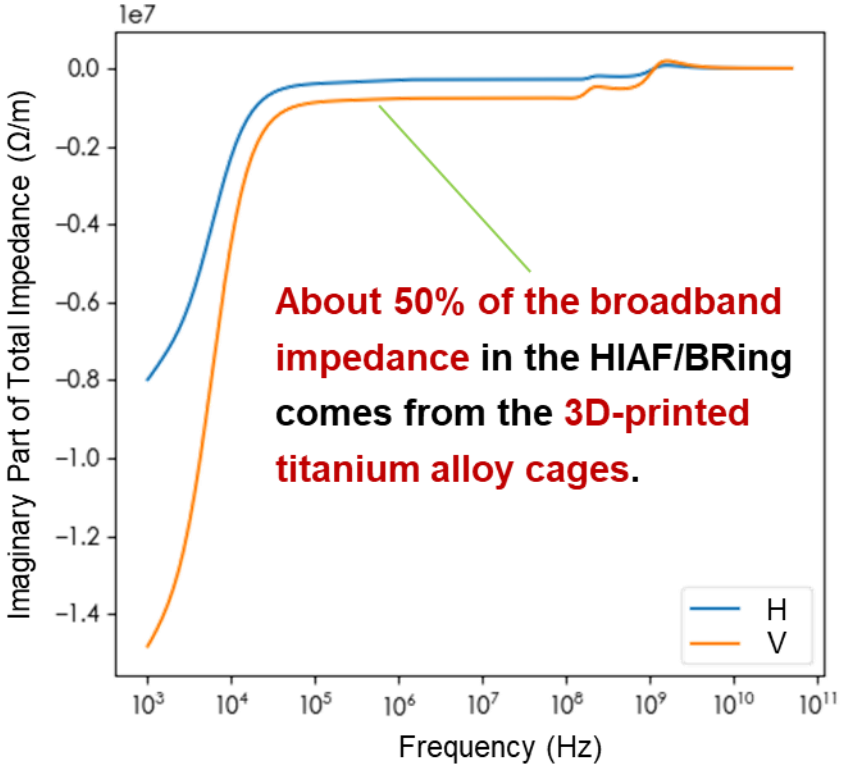


Two Key issues

- **3D-printed titanium alloy cages introduce extra broadband impedances**
- **0.3 mm stainless steel chamber leads to large resistive wall impedance in the low frequencies?**

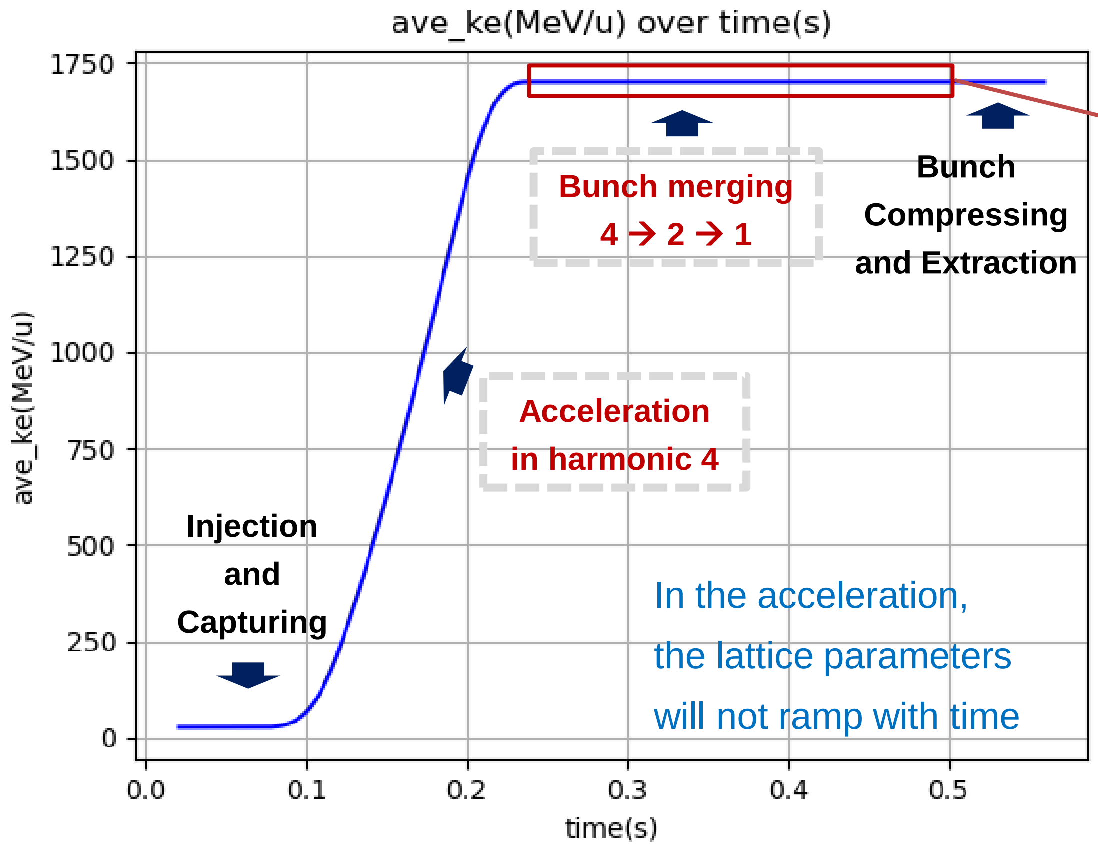


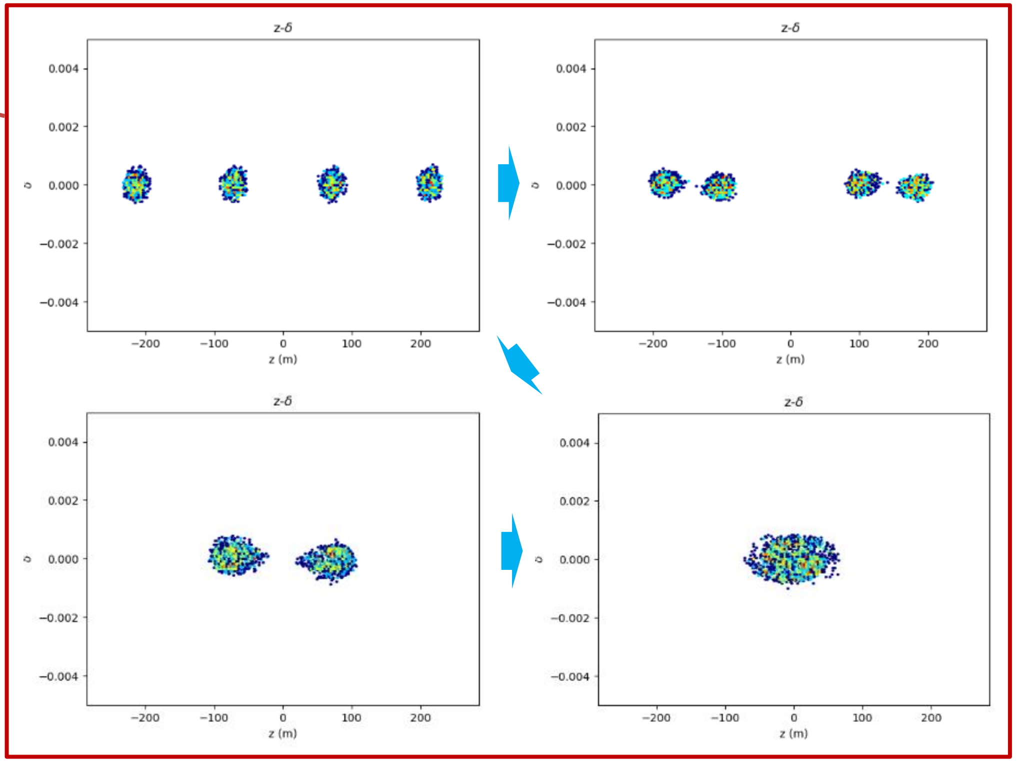


- Resistive wall impedance is calculated by **IW2D**
- Other impedances are simulated by **CST Studio** or calculated by **theory models**.

4. Collective Instabilities – Heavy Ion Beams

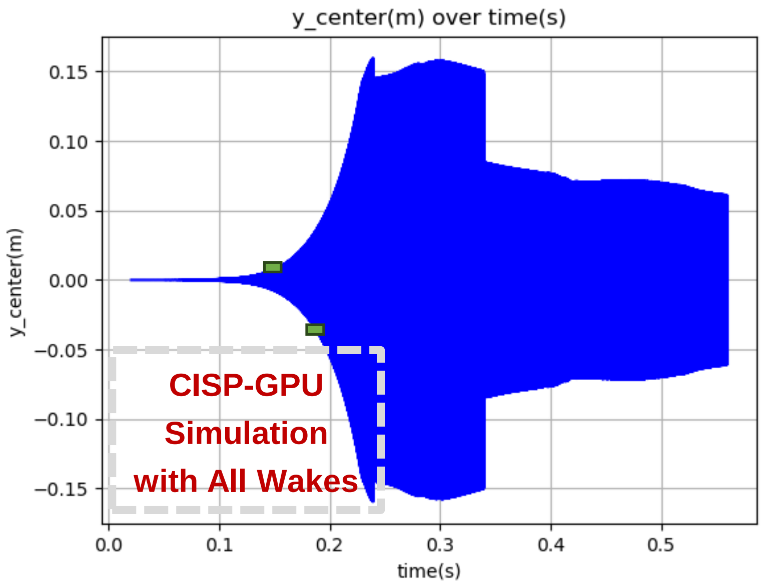
- Heavy ion beams share the same beam manipulations in the HIAF/BRing. **$^{78}Kr^{19+}$ beams have the highest effective intensity Z^2/A**. They are used as reference beams.

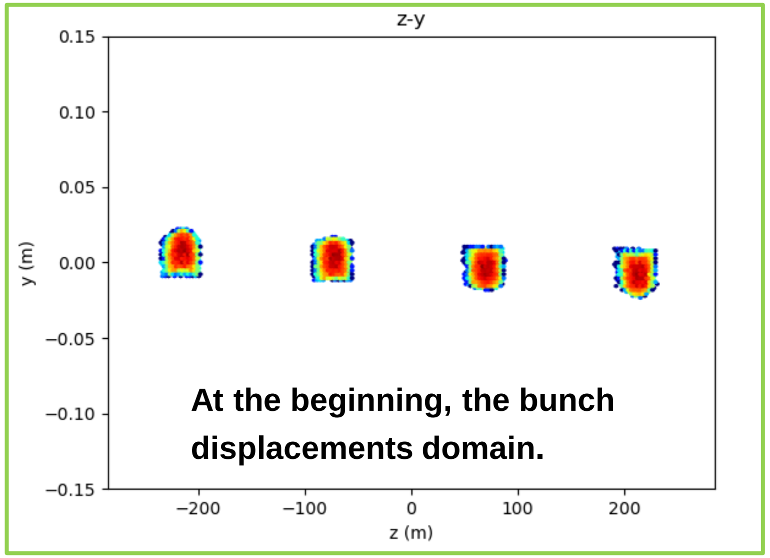


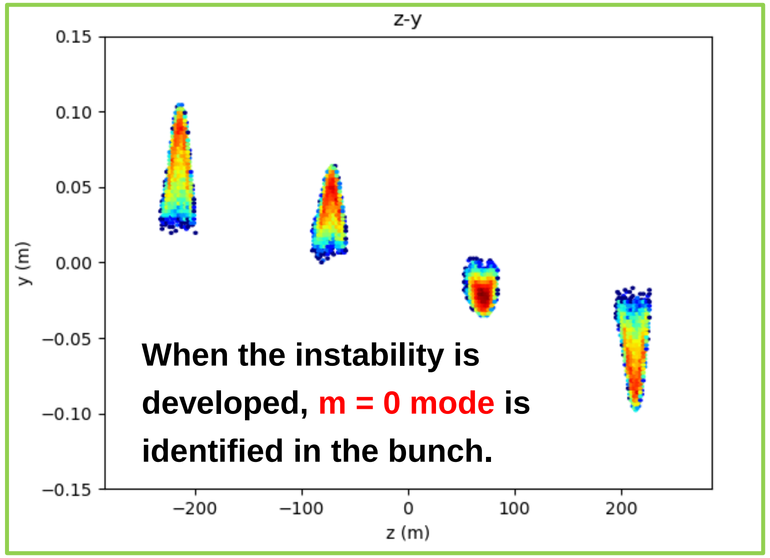


- **If the chromaticity is corrected to 0 as designed**, **transverse mode coupling instability (TMCI)** and **transverse coupled bunch instability (TCBI)** could happen.

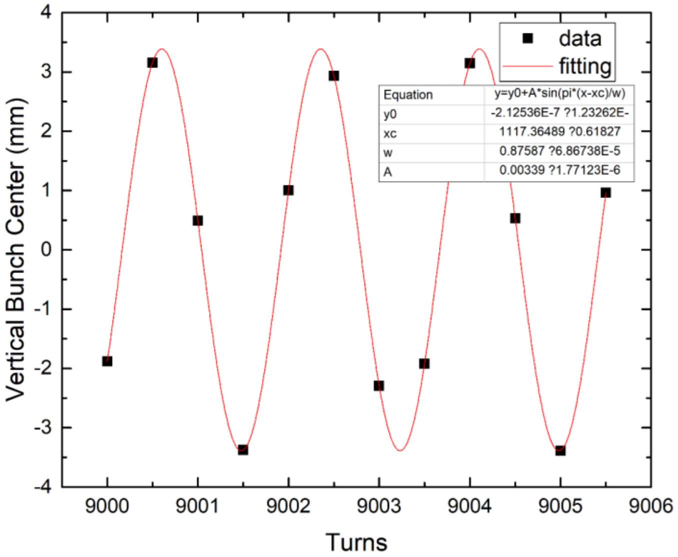
4. Collective Instabilities – Heavy Ion Beams

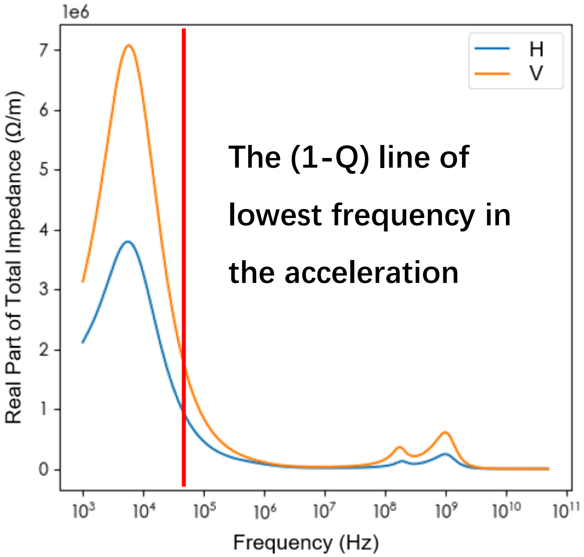






- CISP-GPU shows the TCBI leads to **bunch displacements and beam loss** in the $^{78}Kr^{19+}$ beams.

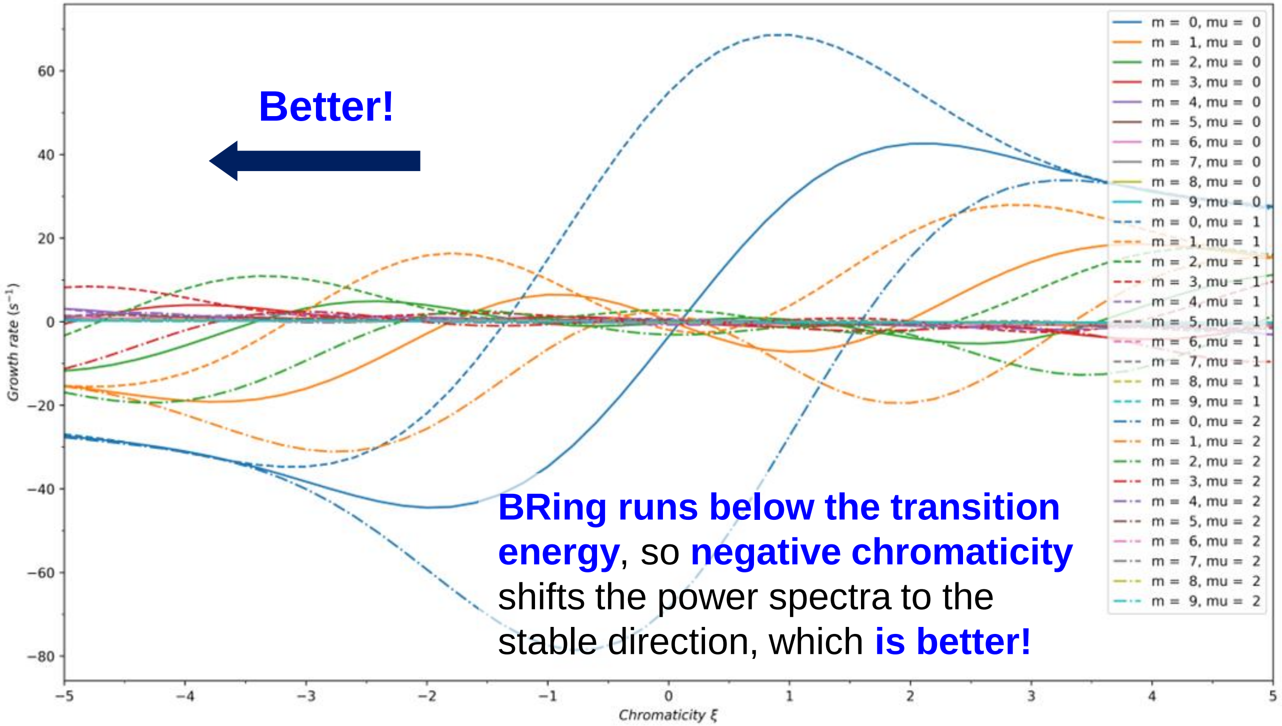


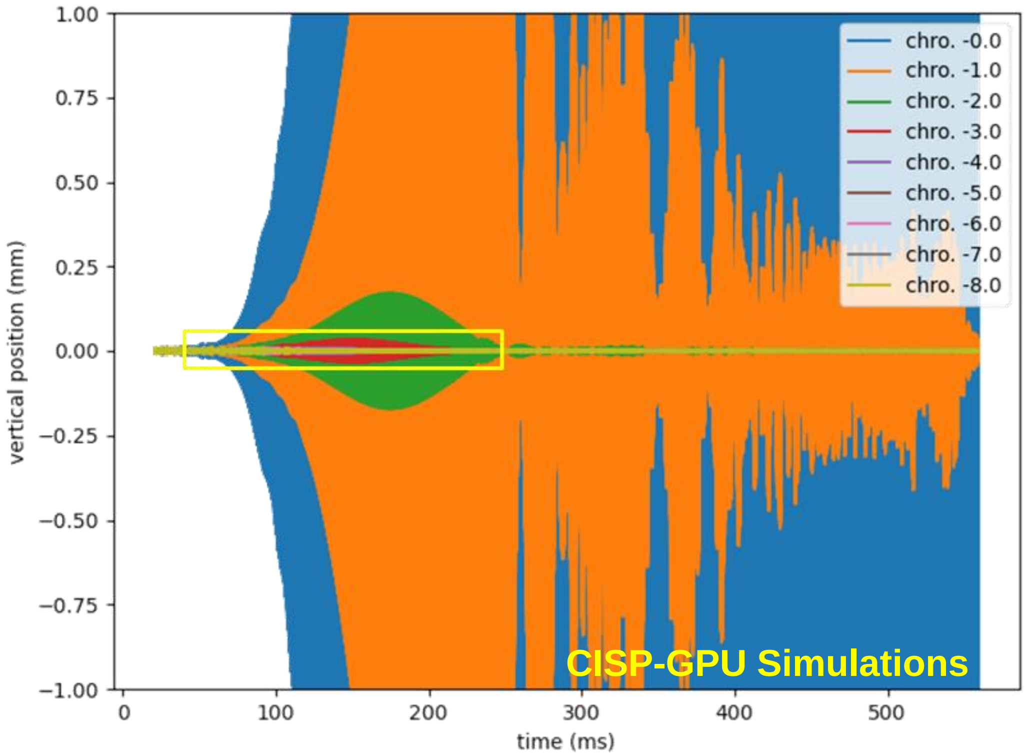


- The phase advance between 2 adjacent bunches is **0.285π in the CISP-GPU simulation**, which agrees with **theory** $(q, \mu, m) = (-3, 2, 0)$ **and** $\Delta\phi = -0.285\pi$.
- **Resistive wall impedance drives the TCBI in the $^{78}Kr^{19+}$ beams of BRing.**

4. Collective Instabilities – Heavy Ion Beams

➢ **1st way to stabilize heavy ion beams – chromaticity**

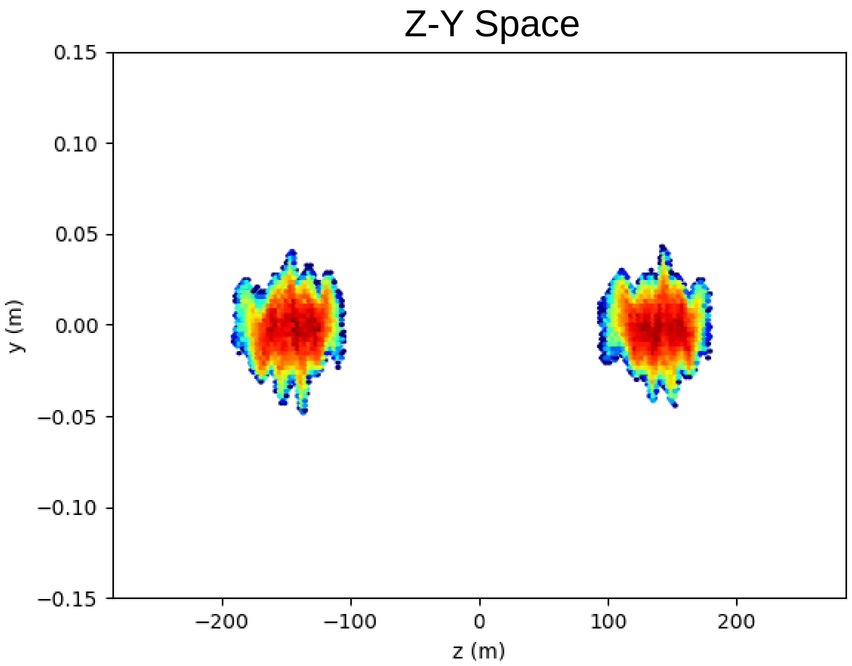




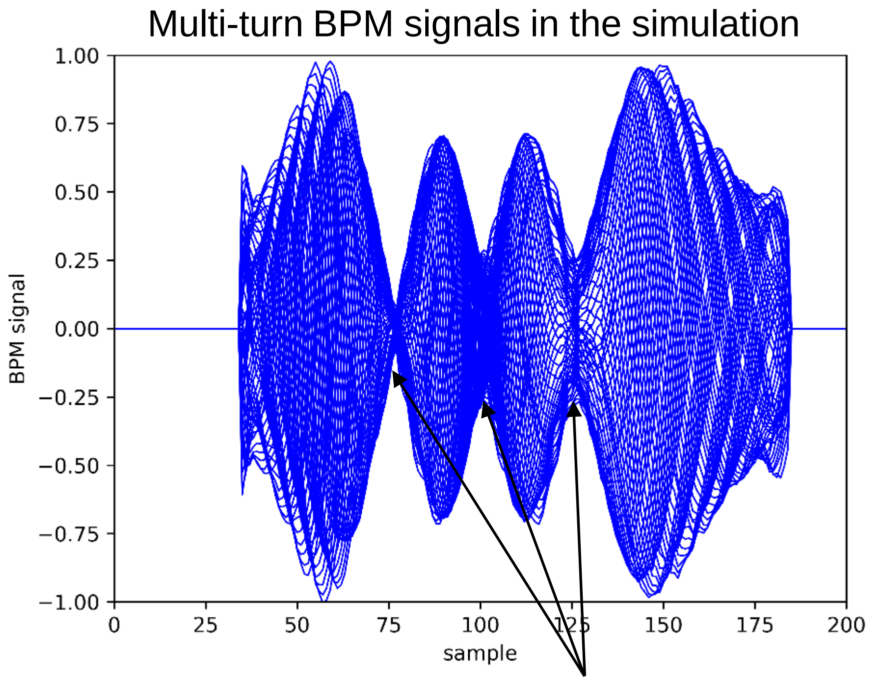
- When $\xi = -4 \sim -5$, the TCBI in the heavy ion beams are **completely stabilized**. The chromaticity is still **less than the natural chromaticity of HIAF/BRing**.
- Adjusting chromaticity is **a feasible and effective way** to stabilize the TCBI.

4. Collective Instabilities – Heavy Ion Beams

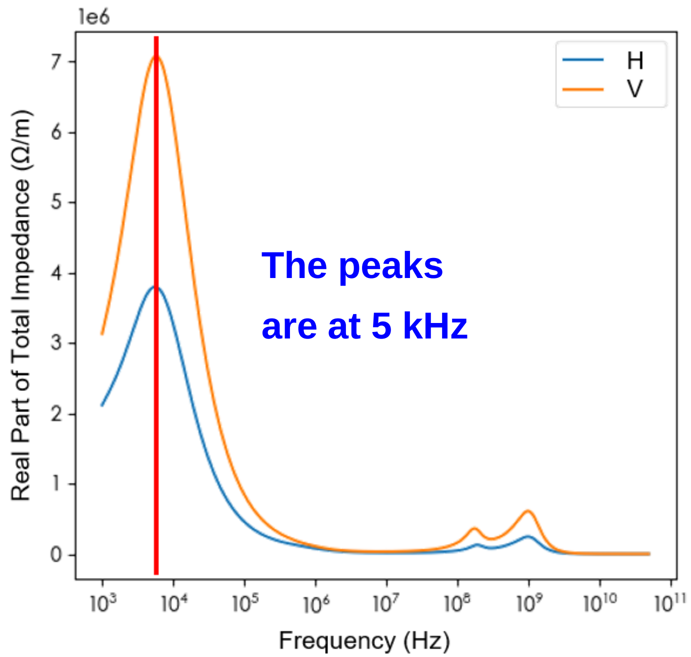
➢ **When adjusting chromaticity, transverse head tail instability may become serious.**



A single-bunch instability



3 nodes means it is a m = 3 high order head tail instability



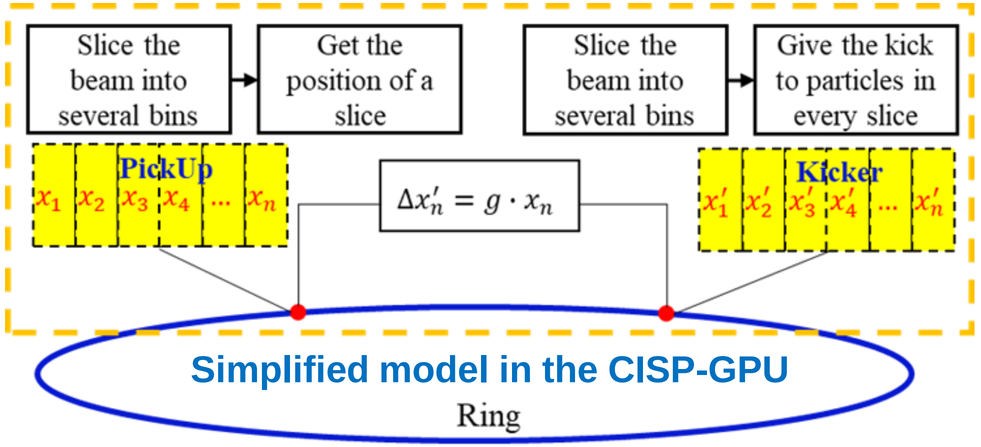
Instability is related to the peak of impedance

- Transverse head tail instability is related to ξ by $\omega_\xi = \frac{\xi\omega_0}{\eta} = -\left[\omega_r - \frac{\pi(m+1)}{\tau_L}\right]^*$
- The peak around frequency of 5 kHz can drive the head tail instability of m = 3 ~ 4, which means **the resistive wall impedance along with ξ drives this instability**. **ξ should be chosen carefully.**

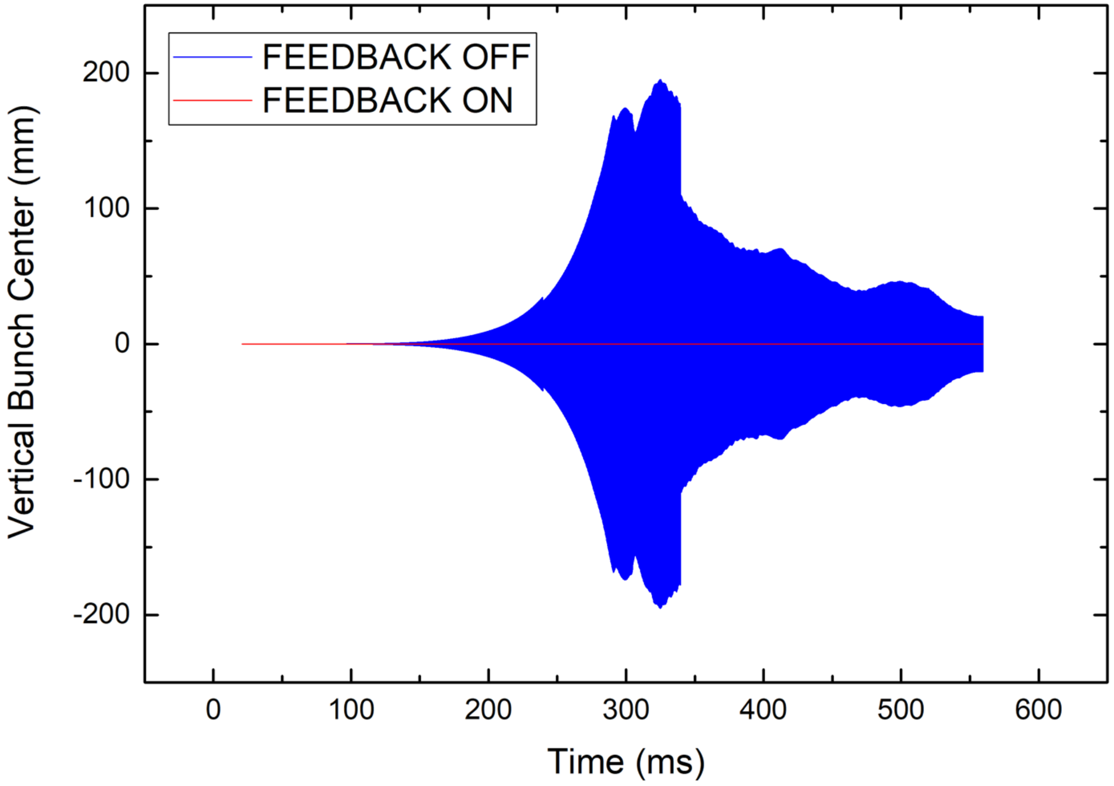
*Physics of Intensity Dependent Beam Instabilities, K. Y. Ng (Fermi National Accelerator Laboratory, USA), World Scientific, December 2005

4. Collective Instabilities – Heavy Ion Beams

➢ **2nd way to stabilize heavy ion beams – wideband feedback system designed for BRing**



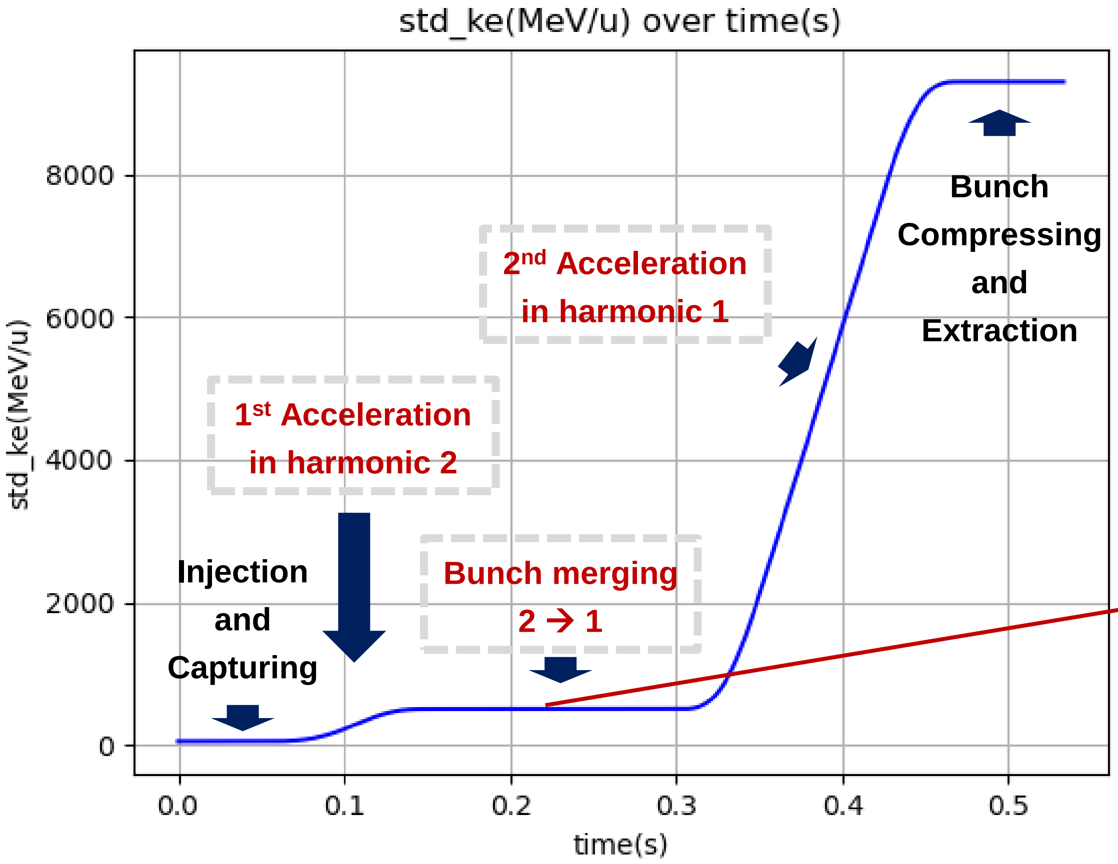
- ✓ Maximal Bandwidth: 40 kHz ~ **100 MHz**
- ✓ Maximal Total Voltage of All Kickers: **20 kV**
- ✓ Delay of Signal from Pickup to Kicker: **1 turn**

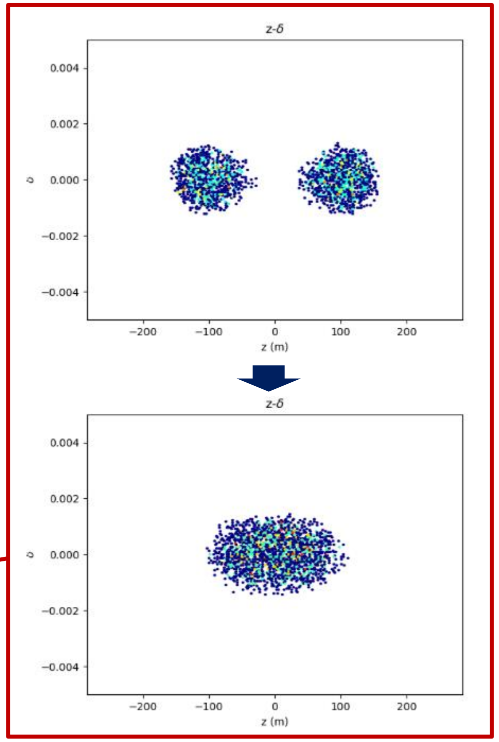


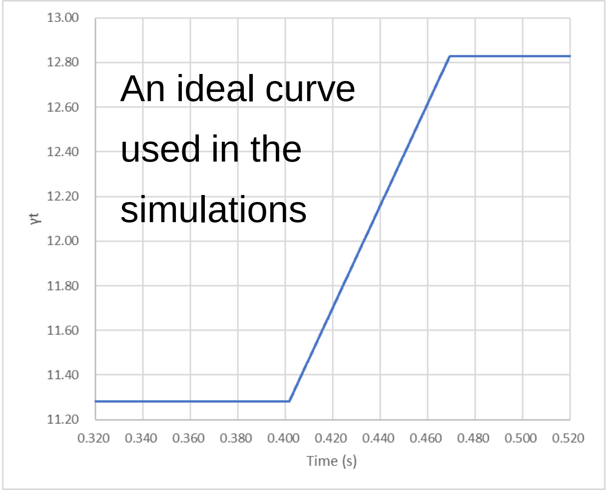
- The wideband feedback system designed for the BRing can stabilize the TCBI in the acceleration process of $^{78}Kr^{19+}$ beams.
- **All heavy ion beams in the BRing could be stabilized by this feedback system.**
- More detailed model will be implemented.

4. Collective Instabilities – Proton Beams

- **Quite different manipulations are designed in the proton beams of HIAF/BRing.**





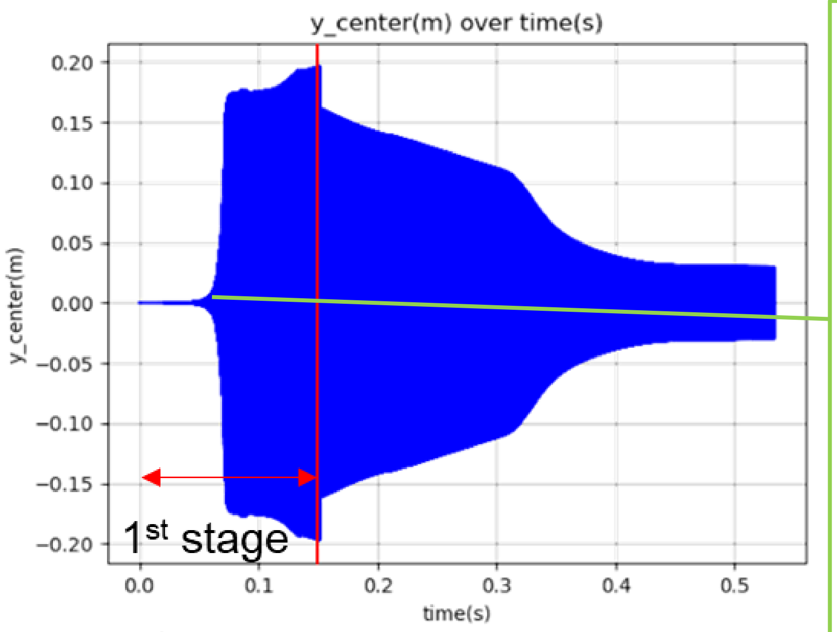


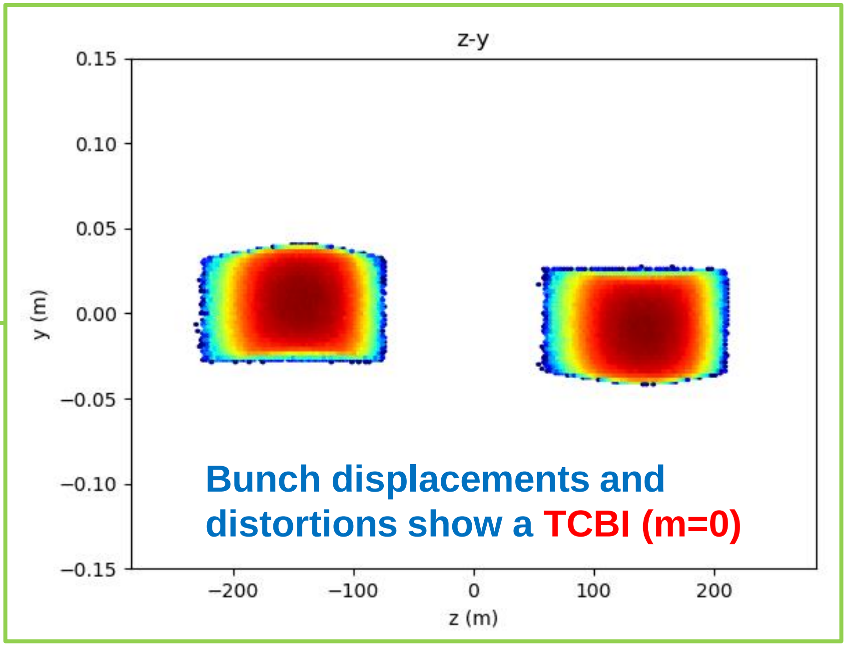
In the 2nd acceleration, γ_t ramps from 11.28 to 12.83, which begins at about 6 GeV.

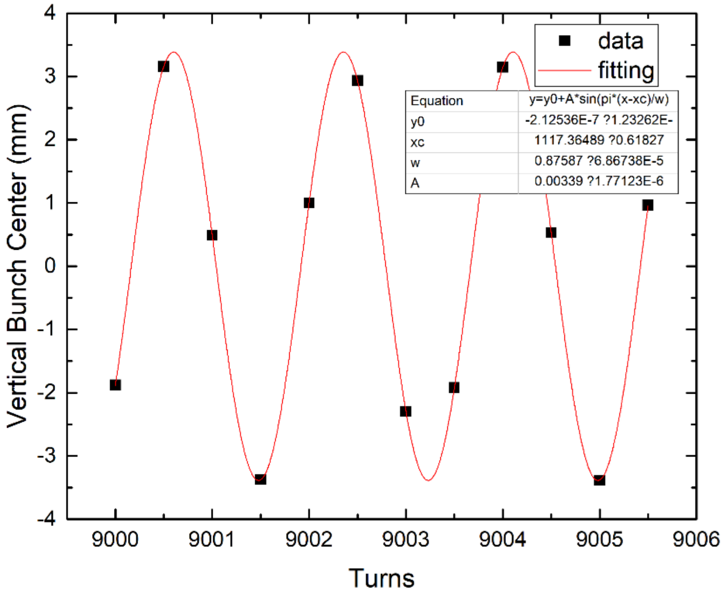
- $\gamma_t = 12.83$ and $\gamma_{beam} = 10.98$ at the extraction, and $\eta = -0.0022$. **It is quite difficult to merge bunches before the extraction in a reasonable time.** Bunch merging is performed at the energy of about **500 MeV**.
- **TCBI may exist in the 1st acceleration and TMCI may exist in all** (quite possible in the 2nd acceleration).

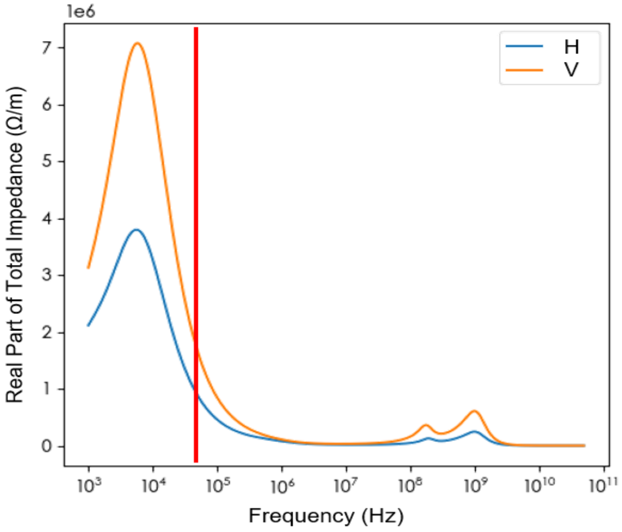
4. Collective Instabilities – Proton Beams

- **In the 1st acceleration, CISP-GPU simulations identify a TCBI.**





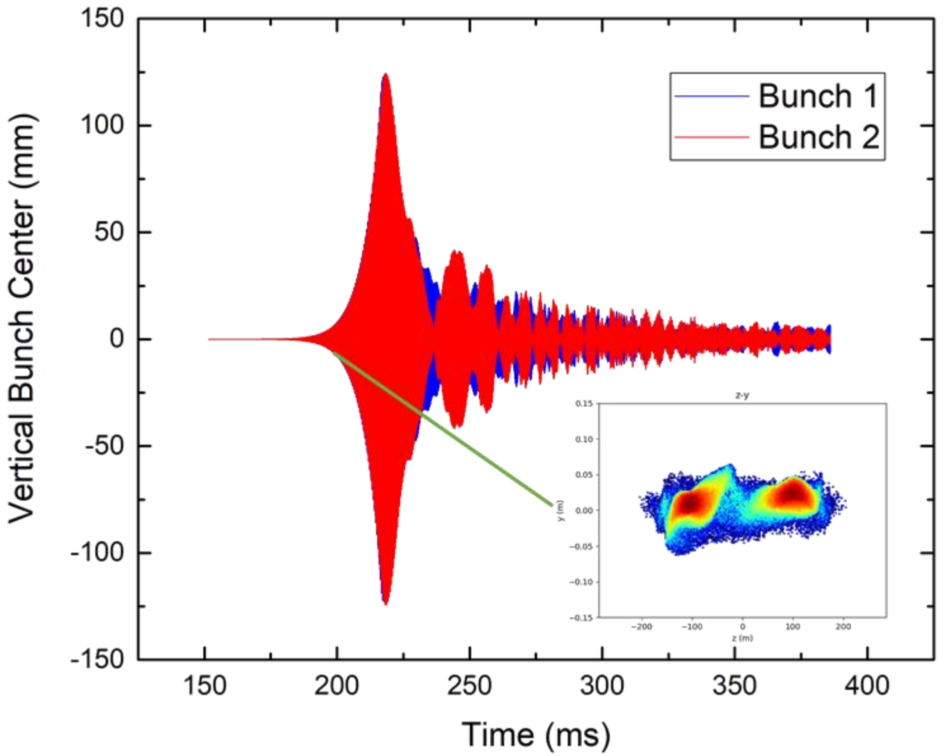




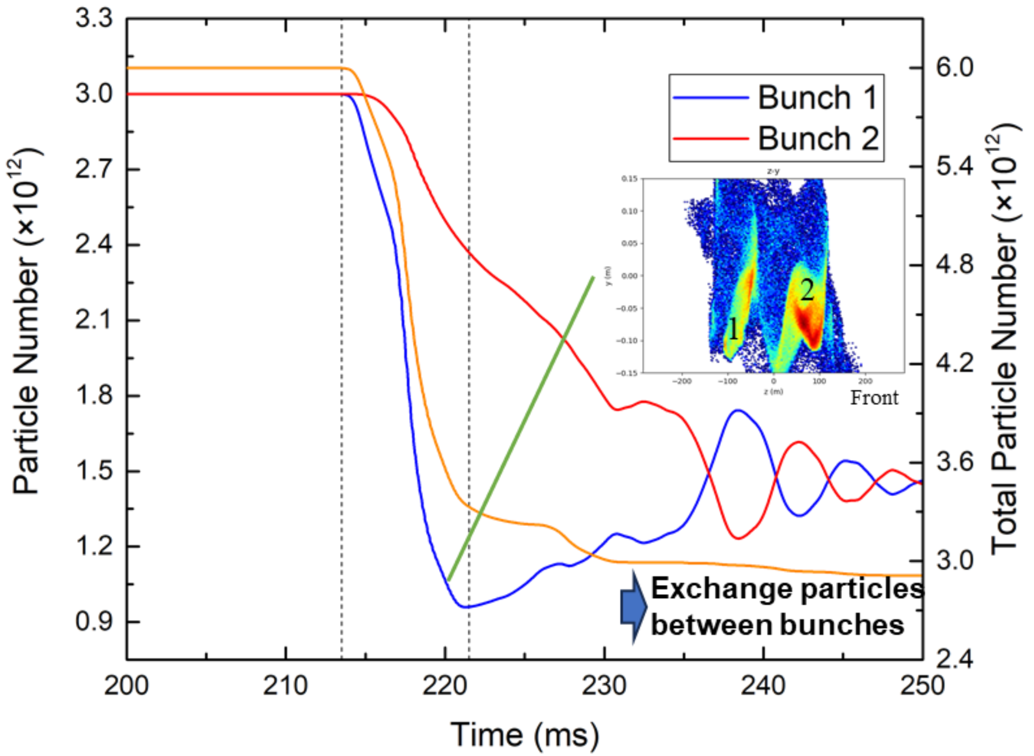
- In the theory, the strongest mode is also at the (1-Q) line, i.e., $(q, \mu, m) = (-5, 0, 0)$ **and** $\Delta\phi_{adj.} = -0.570\pi$.
- The phase advance between 2 adjacent bunches is **0.570π in the simulation**. **Resistive wall impedance could drive the TCBI of the proton beams in the 1st acceleration.**

4. Collective Instabilities – Proton Beams

➢ **In the bunch merging, a special coupled bunch instability is observed via CISP-GPU.**



Both 2 bunches experience similar displacement, which is a TCBI

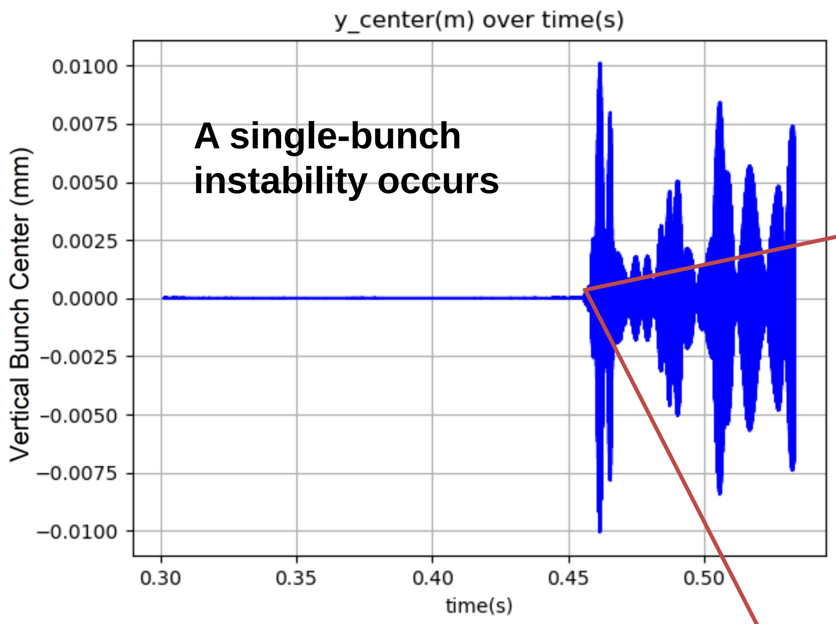


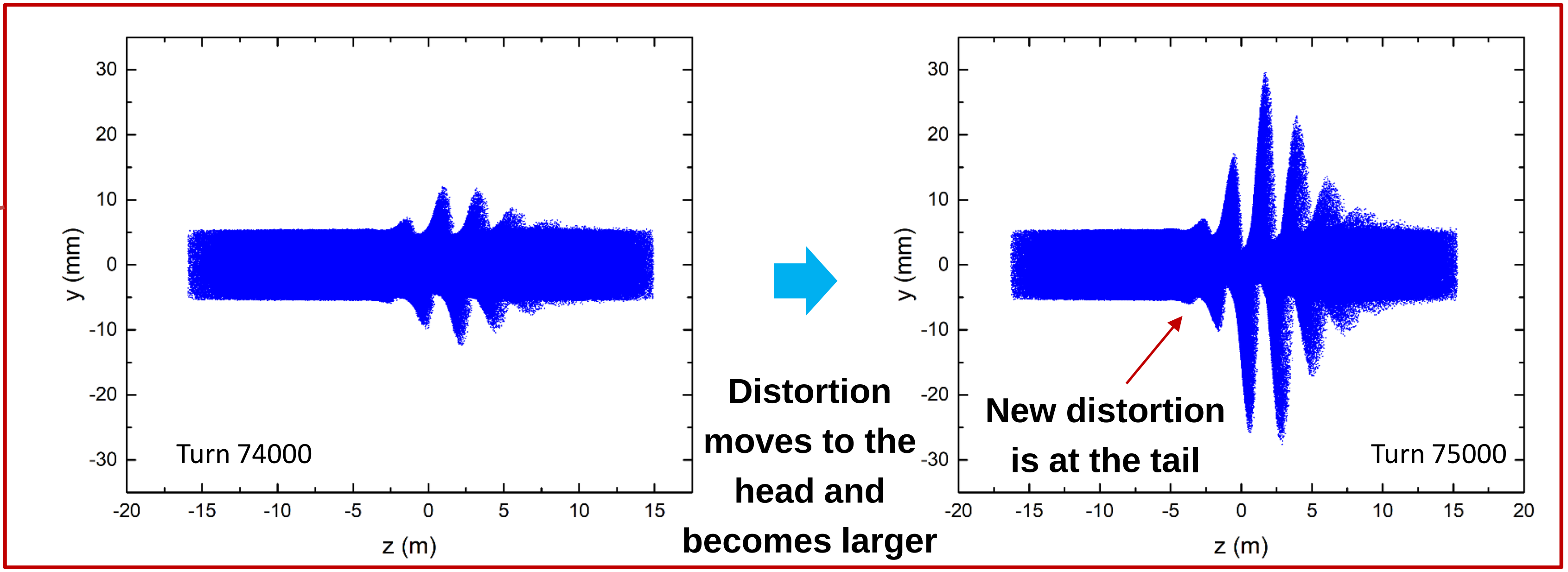
When beam loss becomes serious (between dash lines), **the rear bunch loses much more particles than the front bunch**.

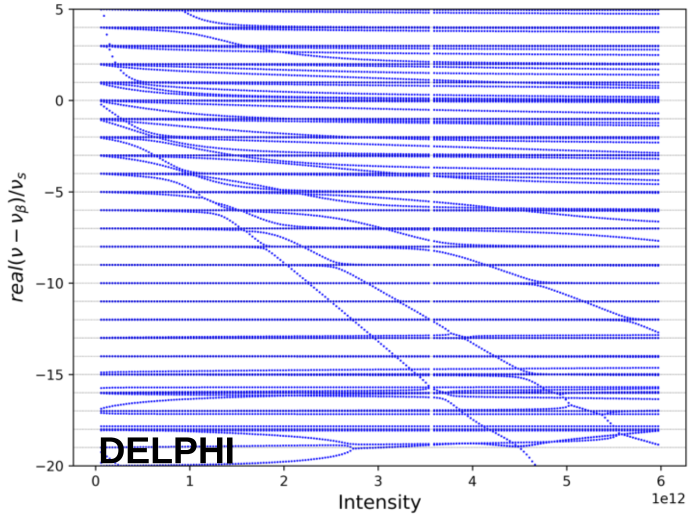
- **In the bunch merging manipulation, the proton beams of HIAF/BRing could be influenced by TCBI**, but the particle loss in the front bunch and the rear one is quite different.

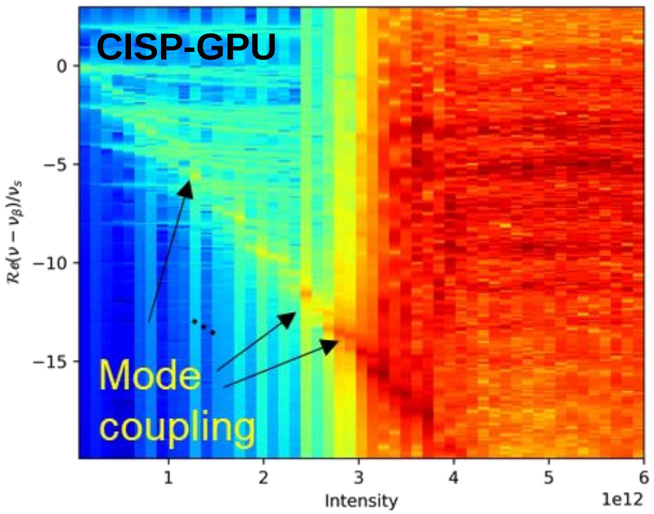
4. Collective Instabilities – Proton Beams

- In the 2nd acceleration, CISP-GPU simulation gives an instability ~ TMCI.





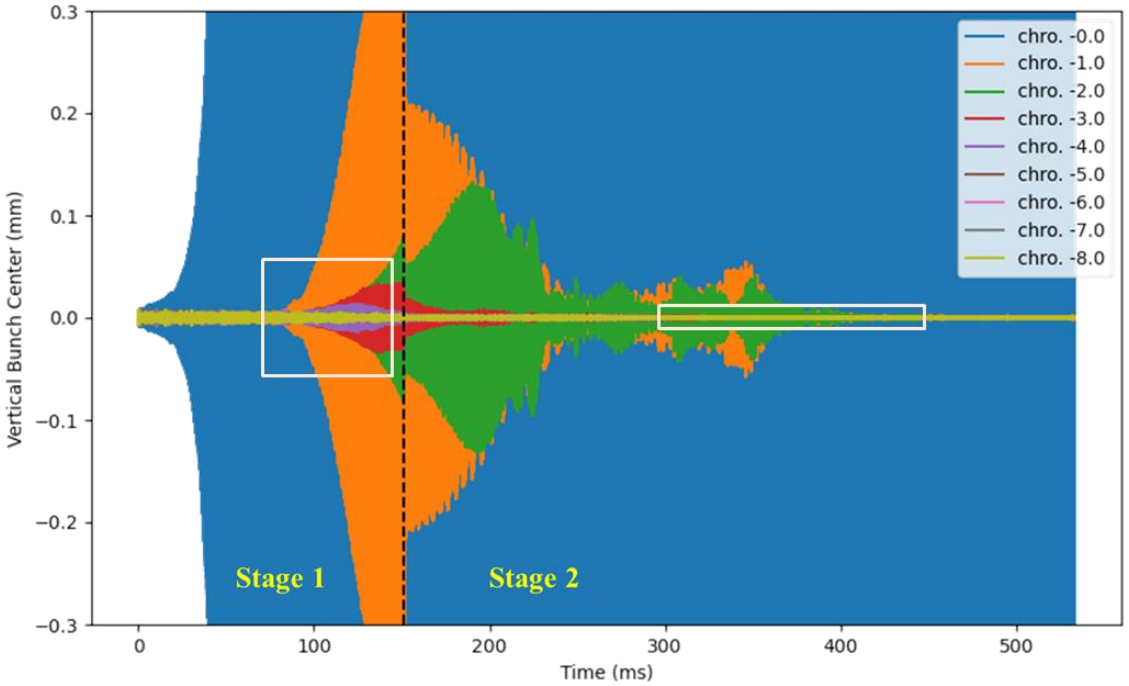




- The synchrotron tune is about 4×10^{-5}, which means **the beam loss happens (in about 5000 ~ 6000 turns) before the distortion at the tail of bunch moves to the head completely.**
- **There are alternatives between coupling and decoupling when intensity increases**, as the bunch is very long while the wake is very short.

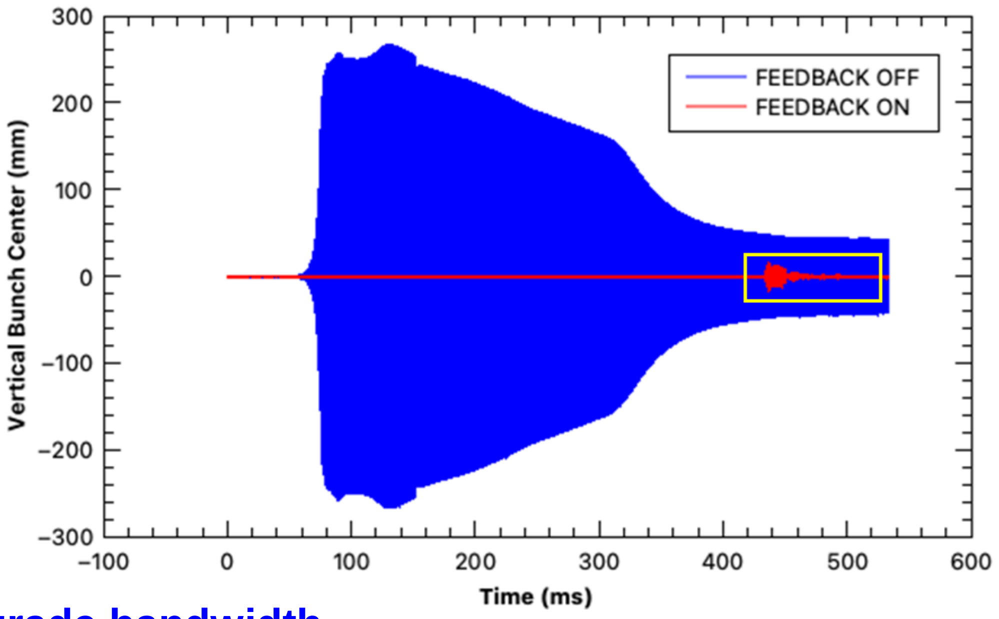
4. Collective Instabilities – Proton Beams

➢ **Chromaticity and wideband feedback system can also stabilize the proton beams.**



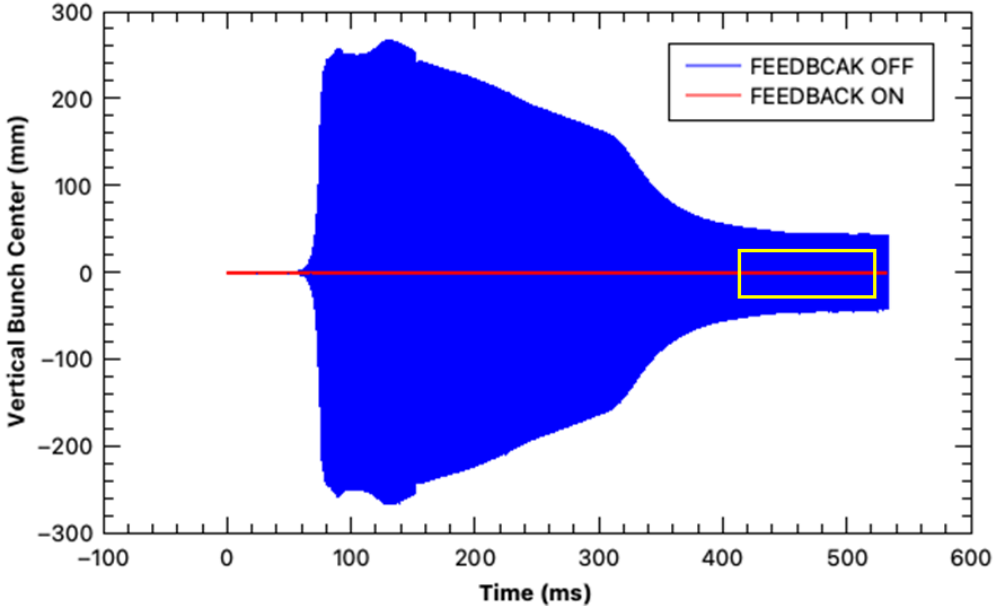
- **The chromaticity is about -5 which is feasible.**
- The bandwidth of wideband feedback system will be **upgraded at least to 500 MHz** in the future.

Bandwidth ~ 100 MHz



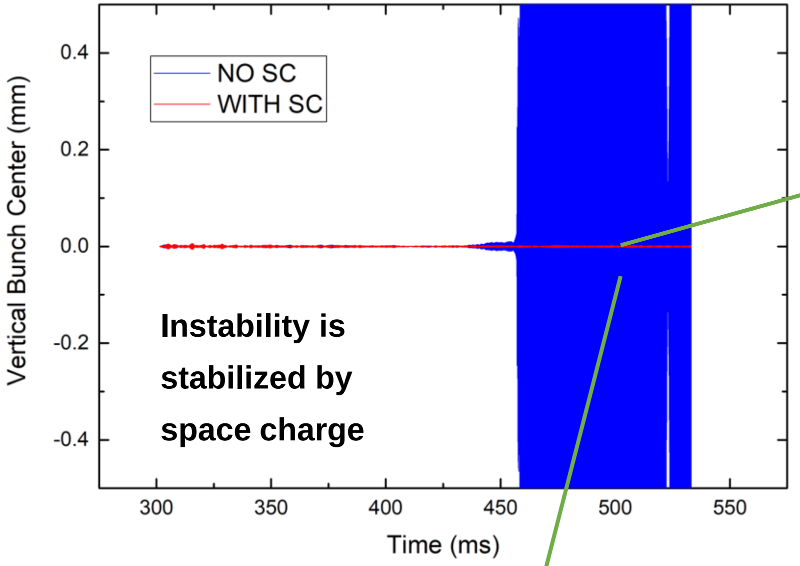
Upgrade bandwidth

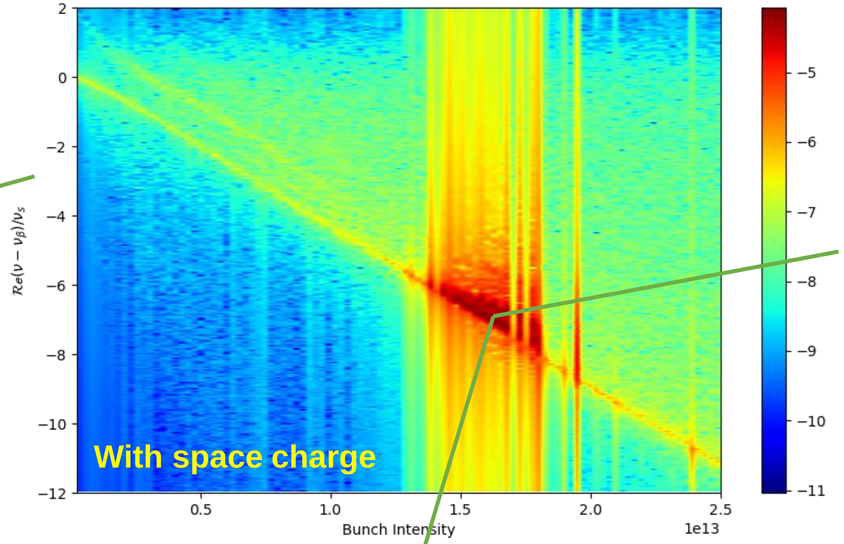
Bandwidth ~ 500 MHz

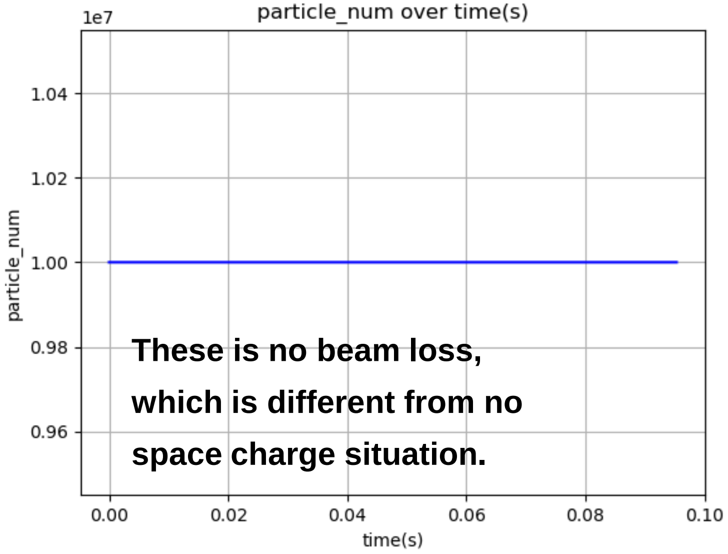


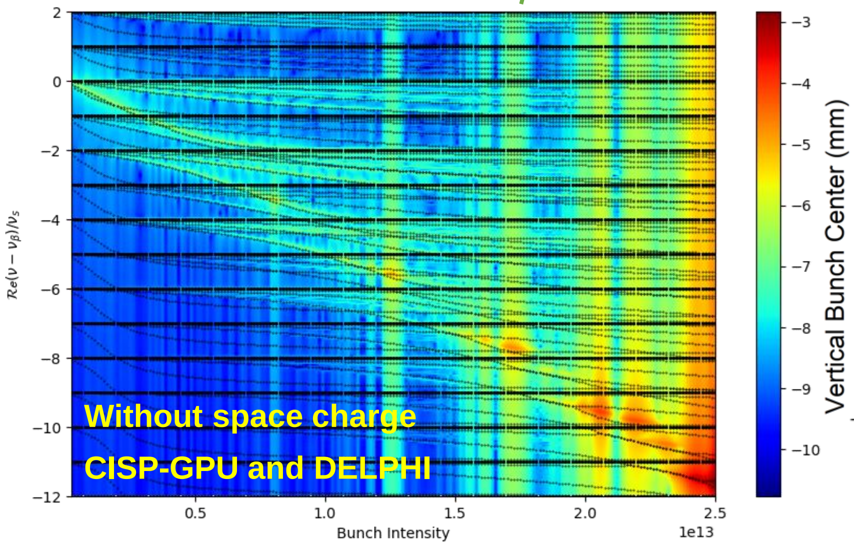
4. Collective Instabilities – Proton Beams

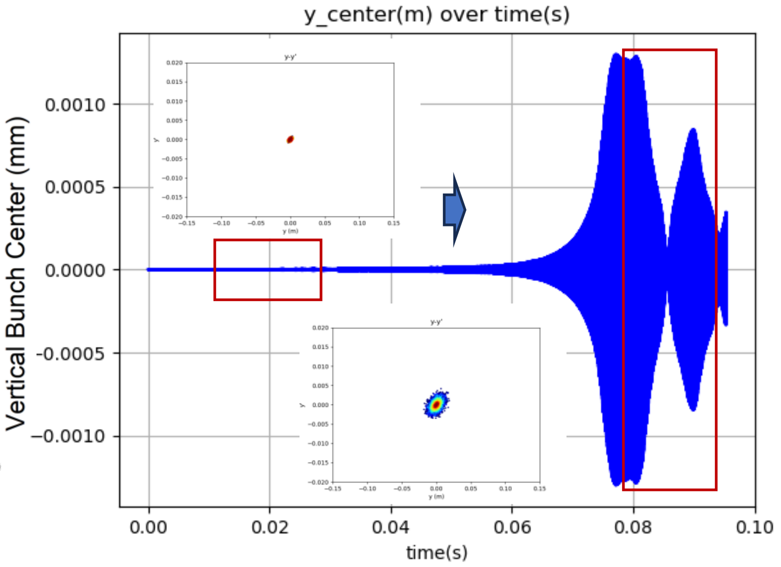
- **Is it possible that the space charge effects in the proton beams stabilize the TMCI?**











- To make the simulation easier, a much larger synchrotron tune (~10x) is set.
- When space charge fields are ignored, mode coupling and beam loss occur.
- **When including space charge, there is no beam loss. Growth still exists, but it disappears after tens of ms.**

Outlines

1. Introduction

2. Development of CISP-GPU

3. Nonlinear and Space Charge Effects

4. Collective Instabilities

5. Conclusions and Discussions

5. Conclusions and Discussion

- A **software platform CISP and its GPU version** are developed to simulate **high intensity effects and their coupling effects in high intensity heavy ion accelerators**.
- **CISP is applied to HIAF/BRing**, which makes the dynamics simulations closer to the actual situations.

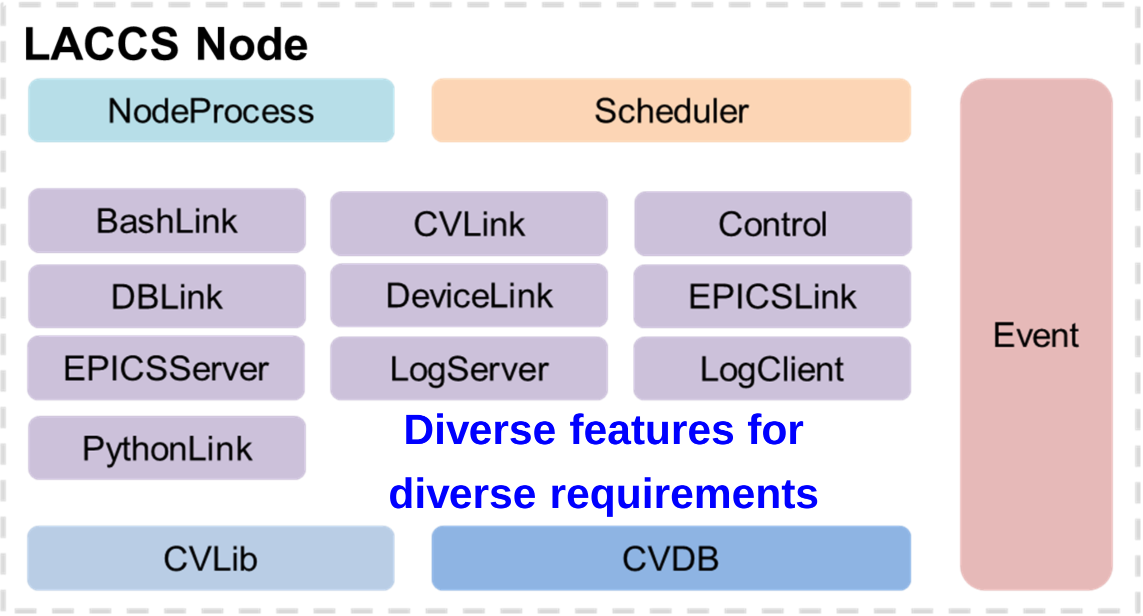
- **The compensation scheme is efficient for 3rd order resonances** from sextupole errors in the zero-intensity situation. It is also feasible for high intensity situation, but how to include space charge needs further research.
- Adjusting tunes is a way to suppress structural resonances but may lead to new problems in other dynamics.

- **Heavy ion beams in the HIAF/BRing will experience transverse coupled bunch instability**. And They could be stabilized by adjusting chromaticity or the wideband feedback system.
- **Transverse coupled bunch instability and transverse mode coupling instability will influence the proton beams in the HIAF/BRing.** They could also be stabilized by adjusting chromaticity. And the band-width of the wideband feedback system should be **upgraded to 500 MHz to stabilize the TMCI** in the future.
- **Space charge can change the modes and stabilize the TMCI in the preliminary simulations.** But how space charge fields interact with broadband impedances in the TMCI of HIAF/BRing is still not clear.

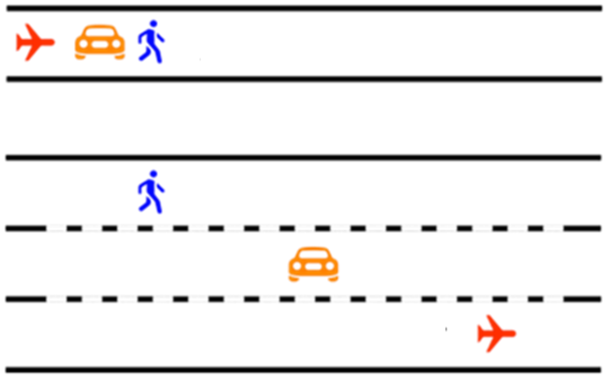
- **Still a lot of work on the way to be ready for the high intensity beam commissioning in the HIAF/BRing!**

5. Conclusions and Discussion

- **A protocol CVLink and its Large-Scale Accelerator Control System LACCS are under development to fulfill total integration, high performance and high intelligent required by HIAF.**



Encryption for high security



Multi-task kernel for high performance

LACCS 大型加速器集群控制 + CISP 强流效应模拟平台

- **In the future, CISP-GPU will be embedded into LACCS to provide high level features for beam commissioning and online dynamics research in the whole HIAF.**

Thanks for your attention!

Any comments or questions?

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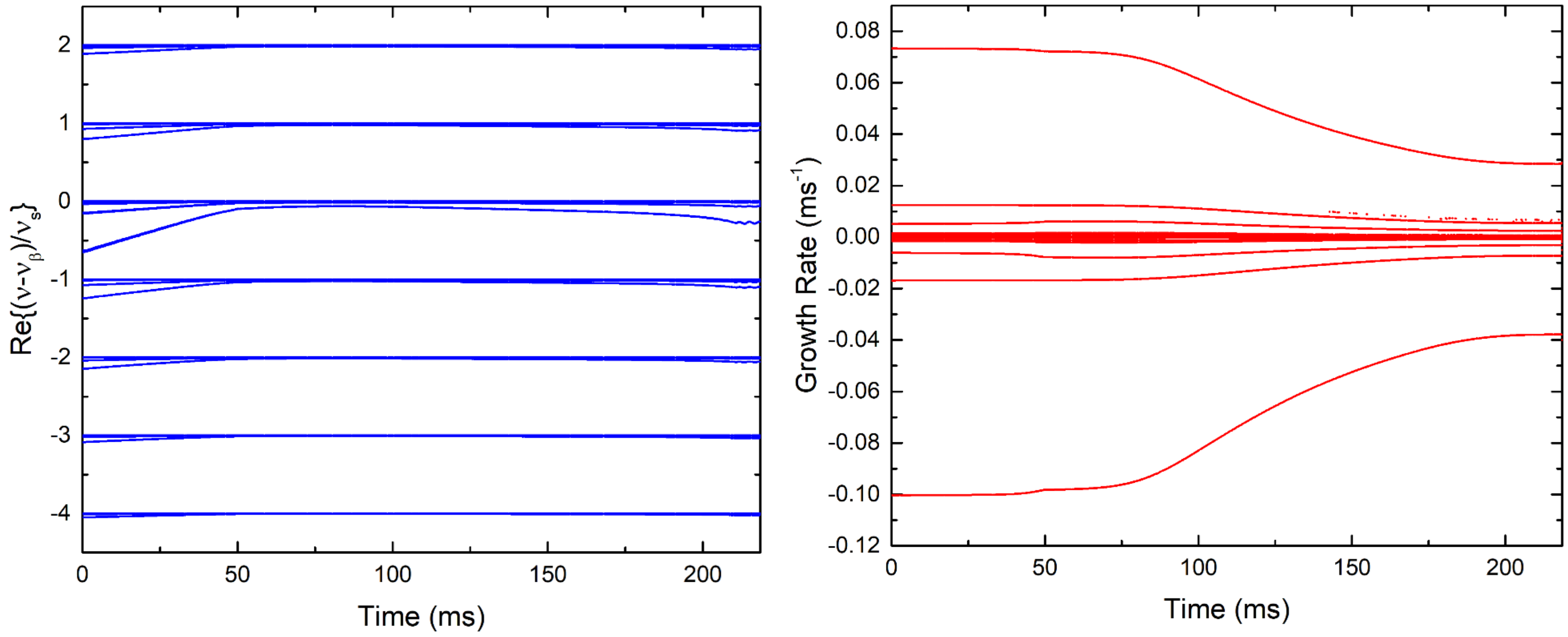
- the National Key R&D Program of China (Grant No. 2019YFA0405400)
- the National Natural Science Foundation of China (NSFC) (Grant No. 11825505)
- the National Natural Science Foundation of China (NSFC) (Grant No. 12005274)

Backups – Heavy ions - DELPHI

- **The mode shifts and growth rates in the acceleration are given by DELPHI.**

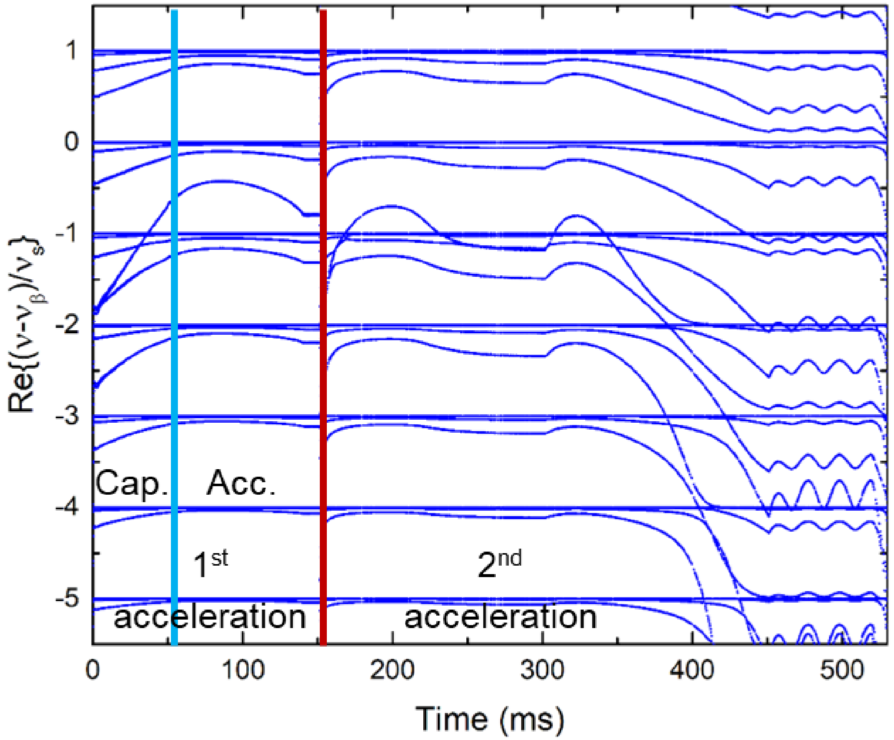


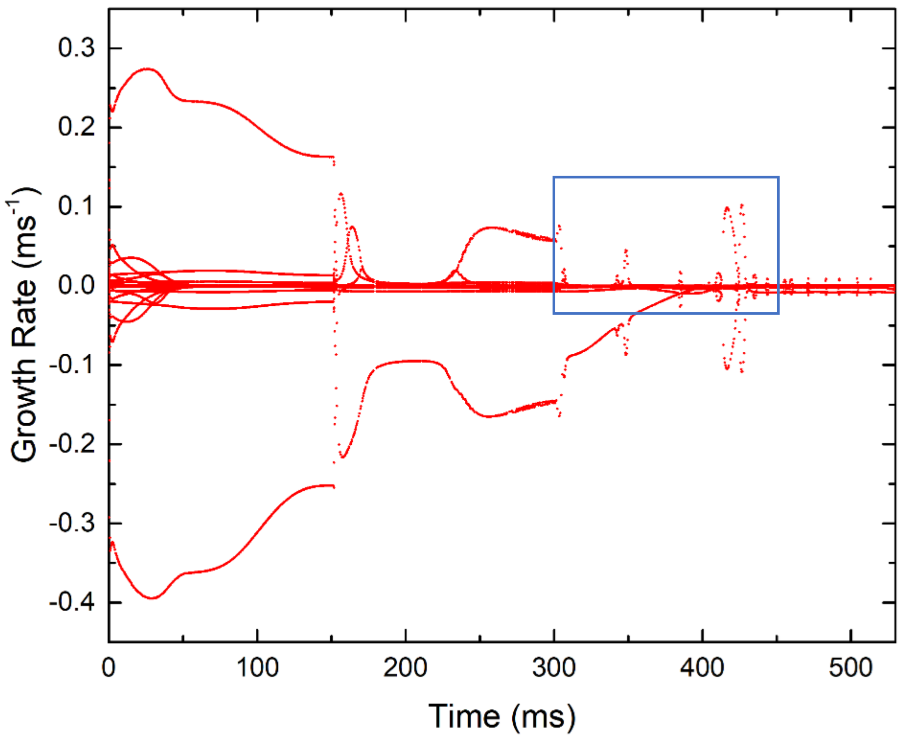
- **No mode coupling**
- **Growth time (< 33 ms) is much shorter** than the required acceleration time (> 200 ms).

- **$^{78}Kr^{19+}$ beams in the HIAF/Bring will just experience TCBI in the acceleration process, which is vital.**
- **Vlasov approach cannot cover the situation beam properties change dramatically**, like bunch merging.

Backups – Protons - DELPHI

➢ **The mode shifts and growth rates in all manipulations are given by DELPHI.**





- **Relatively strong TMCI close to the extraction.**
- As the wake is very short and bunch is very long, it is very difficult to reach numerical convergence.

- **In the 1st acceleration, TCBI** could be the strongest instability.
- **In the 2nd acceleration, TMCI** may exist because there are mode coupling and decoupling.
- **In the bunch merging manipulation, what instability exists is still not clear in the DELPHI results.**