Remarks on combined effects

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With contributions from X. Buffat, M. Zobov, K. Ohmi, and P. Kicsiny

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Why study the combined effects of multiple physical processes?

- Modern particle accelerators deliver high brightness/luminosity to experiments
  - Low emittances ($\epsilon_y \ll \epsilon_x \ll \epsilon_z$), small beta functions at experiments, …
- Multiple physical processes interplay with each other, determining the machine performance (Brightness/Luminosity, Lifetime, Detector background, Injection efficiency, …)
  - Machine imperfections
    - High-order guiding fields (intentional and undesired), Alignment errors, …
  - Incoherent/Coherent collective effects
    - Beam-beam interaction (beamstrahlung), intra-beam scattering, beam-gas/Touschek scattering, impedances, e-cloud/ion/dust, space charge, ISR/CSR, …
  - Beam manipulations
    - Strong focusing (IR of colliders, arc cells of light sources), Crab waist (sext. magnets)/Crab crossing (RF), Strong bunch compression (chicanes of FELs), Various feedbacks (BxB FB for CBIs, orbit feedbacks for experiments), Beam collimation, …
- Studying combined effects (theories, simulations and experiments) has been a prevailing trend over the past two decades (publications plus many talks in this workshop)

Why study the combined effects of multiple physical processes?

Other Factors Affecting Luminosity

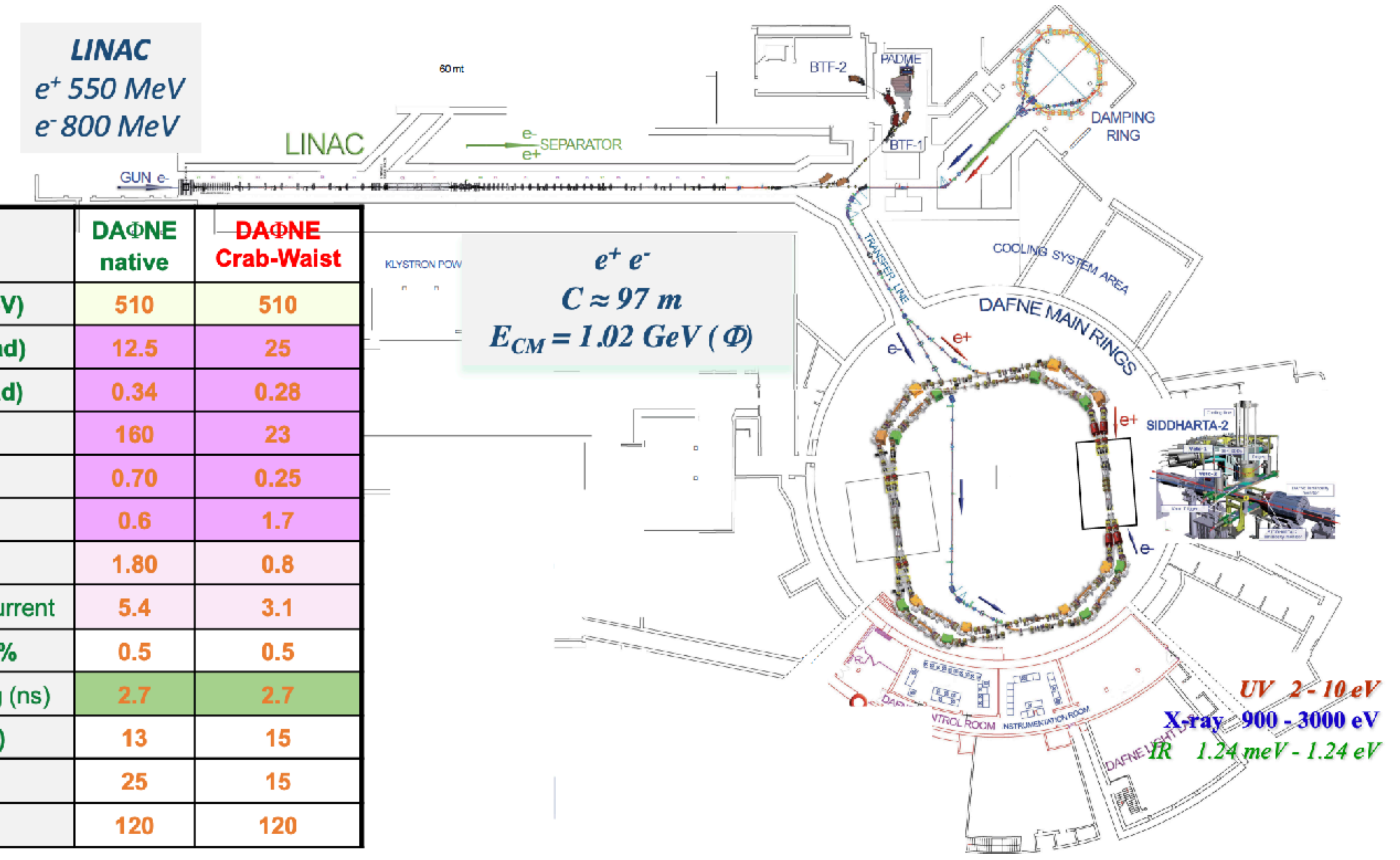
1. Electron cloud (beam size blow up, tune spread)
2. Lattice Nonlinearities
3. Ions of residual gas (incoherent effects, trapped ions)
4. Wake fields (single and multibunch effects)
5. Gap transients (different bunch synchronous phases)
6. Feedback noise (and also in other devices)
7. Low lifetime (not enough time for fine tuning)
8. Space charge effects
9. Touschek scattering
10. Other effects

$1.02^{10} \Rightarrow 1.22$

M. Zobov, IPAC'10, THYRA01

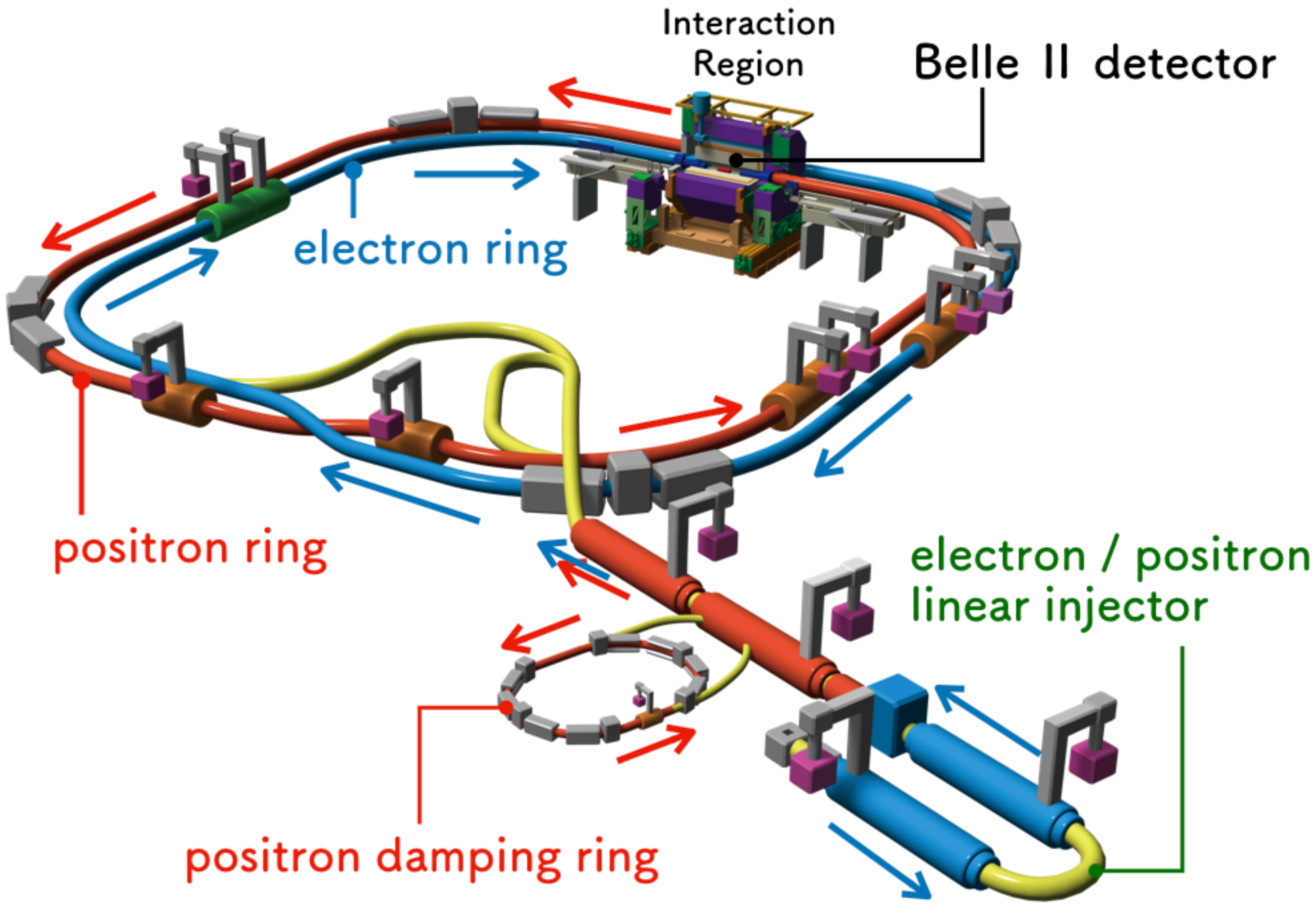
Collider demonstrators for combined effects

- DAFNE (~0.1 km), SuperKEKB (~3 km), and STCF(~1. km) serve as perfect demonstrators for FCCs (~100 km)
  - Collaborations on these projects secure a brighter future of circular e+e- colliders

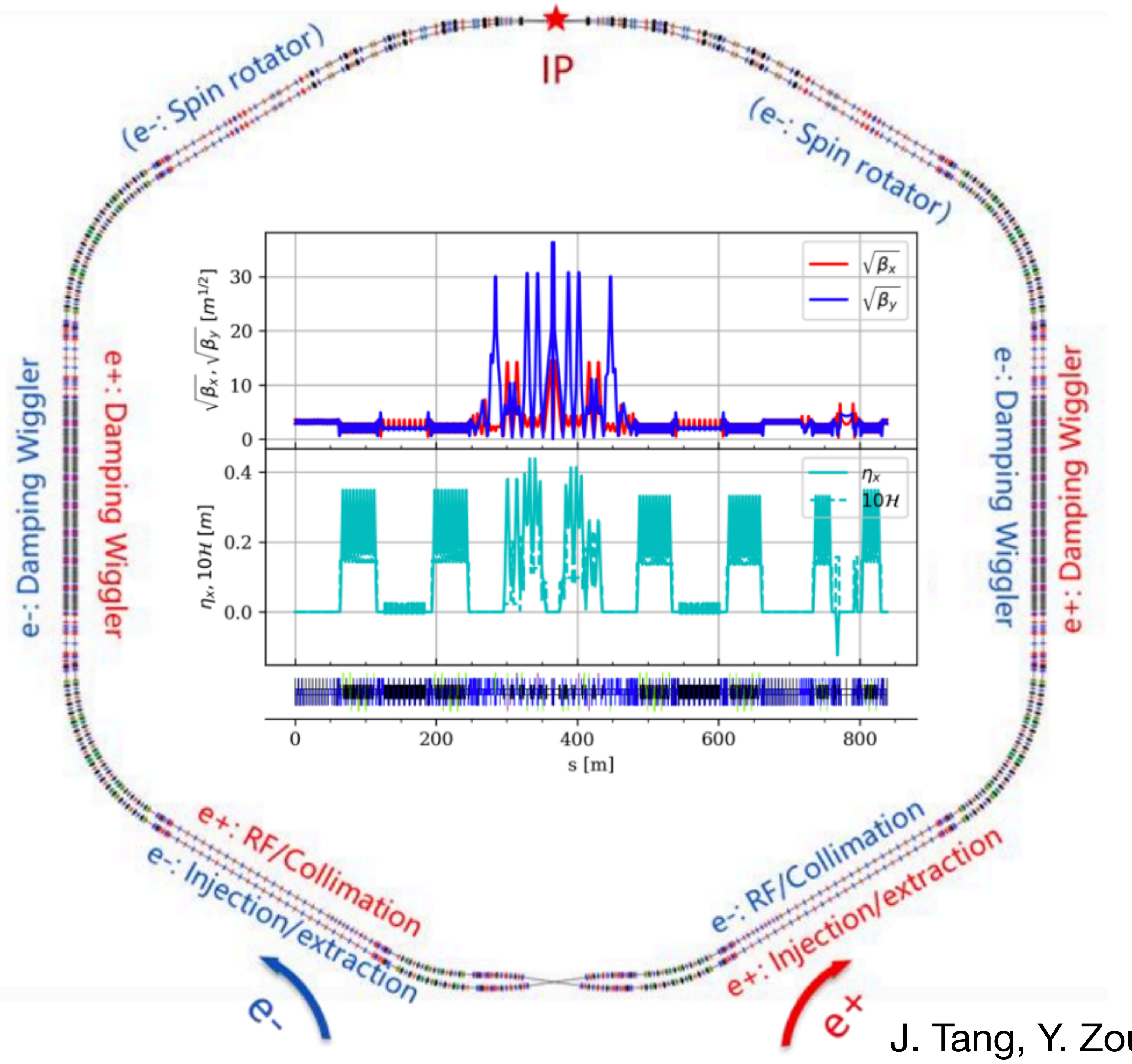


	DAΦNE native	DAΦNE Crab-Waist
Energy (MeV)	510	510
$\theta_{cross}/2$ (mrad)	12.5	25
ε_x (mm•mrad)	0.34	0.28
β_x^* (cm)	160	23
σ_x^* (mm)	0.70	0.25
$\Phi_{Piwinski}$	0.6	1.7
β_y^* (cm)	1.80	0.8
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
Bunch spacing (ns)	2.7	2.7
I_{bunch} (mA)	13	15
σ_z (mm)	25	15
N_h	120	120

C. Milardi (Mon.&Fri.)



Y. Ohnishi, K. Ohmi, et al.



J. Tang, Y. Zou, et al.

Are current theories sufficient to understand combined effects in single-particle dynamics?

- Model of a CW collider ring
  - In terms of Lie maps, the one-turn map is

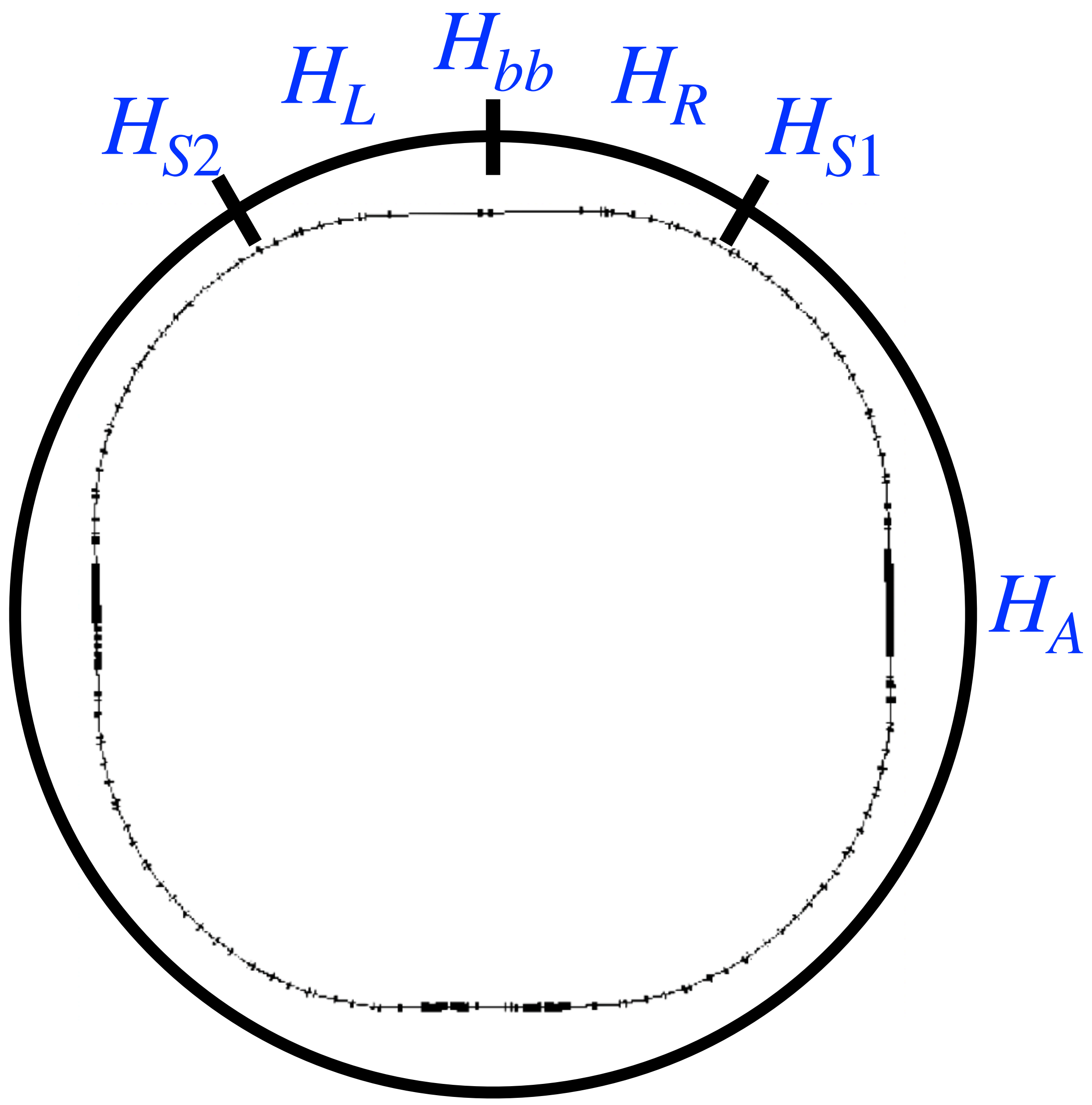
$$M = e^{-:H_R:}e^{-:H_{S1}:}e^{-:H_A:}e^{-:H_{S2}:}e^{-:H_L:}e^{-:H_{bb}:}$$

  - Sequence of elements:
    - H_R, H_L: right and left side of IR
    - H_{S1}, H_{S2}: first and second CW sextupole
    - H_A: arc and straight sections
    - H_{bb}: beam-beam kick at IP
  - The one-turn map of an ideal CW collider ring is

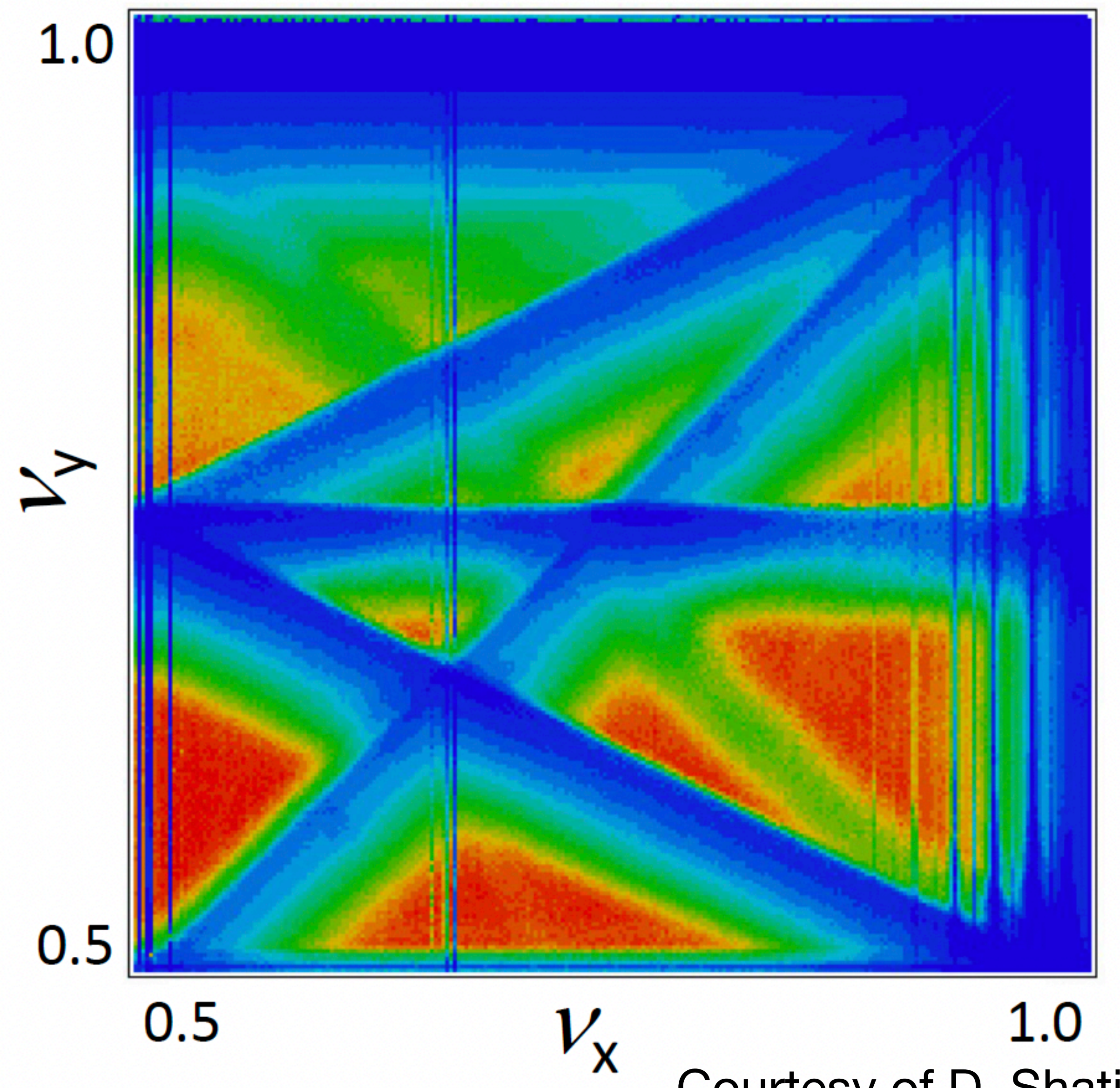
$$M_i = e^{-:H_0:}e^{-:H_{cw}:}e^{-:H_{bb}:}e^{:H_{cw}:} \qquad H_{cw} = \frac{\chi}{2\tan(2\theta_c)}xp_y^2$$

    - χ=1 for full CW strength
    - H_0 is determined only by $\beta^*_{x,y,z}$ and $\nu_{x,y,z}$

- Theoretical studies of single-particle dynamics in CW/CC colliders provide a promising and valuable foundation.



Model of a CW collider by acc. physicists



Courtesy of D. Shatilov

Performance of an ideal CW collider

Theory of beam-beam resonances for ideal CW colliders

- N.S. Dikansky and D.V. Pestrikov, NIM-A 600 (2009) 538-544
  - Beam-beam potential

$$V_{bb} = -\frac{N_0 r_e R_0}{\pi\gamma} \iiint_{-\infty}^{\infty} d\tau dt_x dt_y \frac{\lambda(\tau)}{R_0^2 t_x^2 + t_y^2} e^{it_x(\tau+q_x+\phi_0 q_z)-it_y q_y} e^{-\frac{t_x^2}{2}-\frac{t_y^2}{2}\left(1+\zeta_{x0}^2(\tau+\phi_0 q_z)^2\right)}$$

$$\lambda(\tau) = \frac{1}{\sqrt{2\pi}\phi_0} e^{-\frac{\tau^2}{2\phi_0^2}}$$

$$\zeta_{x0} = \sigma_{x0}^* / (\beta_{y0}^* \tan(2\theta_c))$$

$$R_0 = \sigma_{y0}^* / \sigma_{x0}^*$$

  - Equations of motion for the weak-beam particles

$$x = \sqrt{2\beta_x^* J_x} \cos\psi_x, \quad y(s') = \sqrt{2\beta_y(s') J_y} \cos\phi_y(s'), \quad z = \sqrt{2\beta_z J_z} \cos\psi_z$$

* Simplest equations of motion around IP

* Can be extended to include many effects (coupling, dispersion, chromaticity, impedance effects, …)

Also see K. Ohmi's talk this morning

  - Hourglass effect and CW transform

$$\beta_y(s') = \beta_y^* \left(1 + \frac{1}{\beta_y^{*2}}\left(s' + \frac{\chi x}{\tan(2\theta_c)}\right)^2\right), \quad \phi_y(s') = \psi_y + \arctan\left(\frac{s' + \frac{\chi x}{\tan(2\theta_c)}}{\beta_y^*}\right)$$

  - Beam-beam resonances

$$V_{bb}\delta(\theta) = \sum_{\vec{m},n} V_{m_x m_y m_z} e^{i(m_x\psi_x + m_y\psi_y + m_z\psi_z - n\theta)}, \quad V_{m_x m_y m_z} = \frac{1}{(2\pi)^4} \iiint_0^{2\pi} d\psi_x d\psi_y d\psi_z V_{bb} e^{-i(m_x\psi_x + m_y\psi_y + m_z\psi_z)}$$

- The theory establishes a solid foundation for weak-strong beam-beam studies in CW colliders (see C. Milardi's talks).

Are current theories sufficient to understand collective instabilities with combined effects?

- Most of the (semi-)analytic theories on collective instabilities are based on Sacherer formalism (1972) and its extensions
  - Mode expansion approach
  - Inclusion of wakefields, beam-beam, space charge, chromaticity, … and their combinations
  - Estimate of growth rate and threshold current
- Exploring collective instabilities in CW/CC colliders offers another fruitful and essential avenue.
  - See next page and summary talk by R. Thomas and X. Buffat

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METHODS FOR COMPUTING BUNCHED-BEAM INSTABILITIES

by

F. Sacherer

Combined effects of beam-beam and others

K. Ohmi

- Beam-beam, Impedance, Space charge, Lattice nonlinearity.
- Horizontal and vertical beam-beam instabilities are driven by beam-beam cross-wake forces. The tune dependence of these instabilities arises from the localized nature of the interaction. Specifically, tunes just above a half-integer are susceptible to low-order synchrotron sideband instabilities.
  - K.Ohmi et al., PRL 119, 134801 (2017).
- Longitudinal impedance causes potential well (longitudinal phase space) distortion. The distortion affects the beam-beam (X-Z) instability.
  - Y. Zhang et al., PRAB 23, 104402 (2020). C. Lin et al., PRAB 25, 011001 (2022). D. Zhou et al., PRAB 26, 071001 (2023).
- A positive tune shift for synchrotron sidebands is caused by the cross-wake, and a negative tune shift for the 0 mode is caused by impedance. The combined effect of these opposing tune shifts reduces the threshold for TMCI.
  - Y. Zhang et al., PRAB 26, 064401(2023).
- The beam-beam cross-wake exhibits a similar effect to space charge in the vertical plane, differing primarily in its localized versus uniform distribution. Space charge weakens TMCI-like beam-beam instability, but can enhance localized beam-beam (Y-Z) instability.
  - K.Ohmi et al., PRAB 27, 101001 (2024).

Are current tools sufficient to model combined effects in CW colliders?

- More and more codes have been extended to model combined effects
- Code development for CW/CC colliders presents a crucial and impactful direction.

	Weak-strong 6D	Quasi-strong-strong 6D	Strong-strong 6D SG	Strong-strong 6D PIC	Beamstrahlung	Bhabha-scattering	Transverse wakefields	Longitudinal wakefields	Linear tracking	Lattice tracking	Perturbation maps	Space charge	Open source	Runs on GPU
GUINEA-PIG	Available	Not available	Not available	Available	Available	Available	Not available	Not available	Not available	Not available	Not available	Not available	Available	Not available
COMBI	Available	Available	Available	Available	Not available	Not available	Available	Not available	Available	Not available	Not available	Not available	Available	Not available
BBWS	Available	Not available	Not available	Not available	Available	Not available	Available	Available	Available	Not available	Available	Not available	Not available	Not available
BBSS	Not available	Not available	Available	Available	Available	Not available	Available	Available	Available	Not available	Available	Not available	Not available	Not available
BBSCL (old SCTR)	Not available	Not available	Available	Available	Available	Not available	Available	Available	Available	Available	Available	Available	Not available	Available
IBB	Not available	Not available	Available	Not available	Available	Not available	Available	Available	Available	Not available	Available	Available	Not available	Not available
LIFETRAC	Available	Available	Not available	Not available	Available	Not available	Not available	Not available	Available	Available	Available	Not available	Not available	Not available
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Xsuite	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Not available	Available	Available	Available
APES-T	Not available	Not available	Available	Available	Available	Not available	Available	Available	Available	Available	Available	Not available	Not available	Available
(Sci)Bmad/PTC	Available	Not available	Not available	Not available	Not available	Not available	Available	Available	Available	Available	Available	Available	Available	Not available
SAD	Available	Not available	Not available	Not available	Available	Not available	Available	Available	Available	Available	Available	Available	Available	Not available

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Please contact P. Kicsiny
for any corrections/extensions

Extended table of
P. Kicsiny (BB24 workshop)

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