Status of impedance modelling and collective effects for PETRA IV

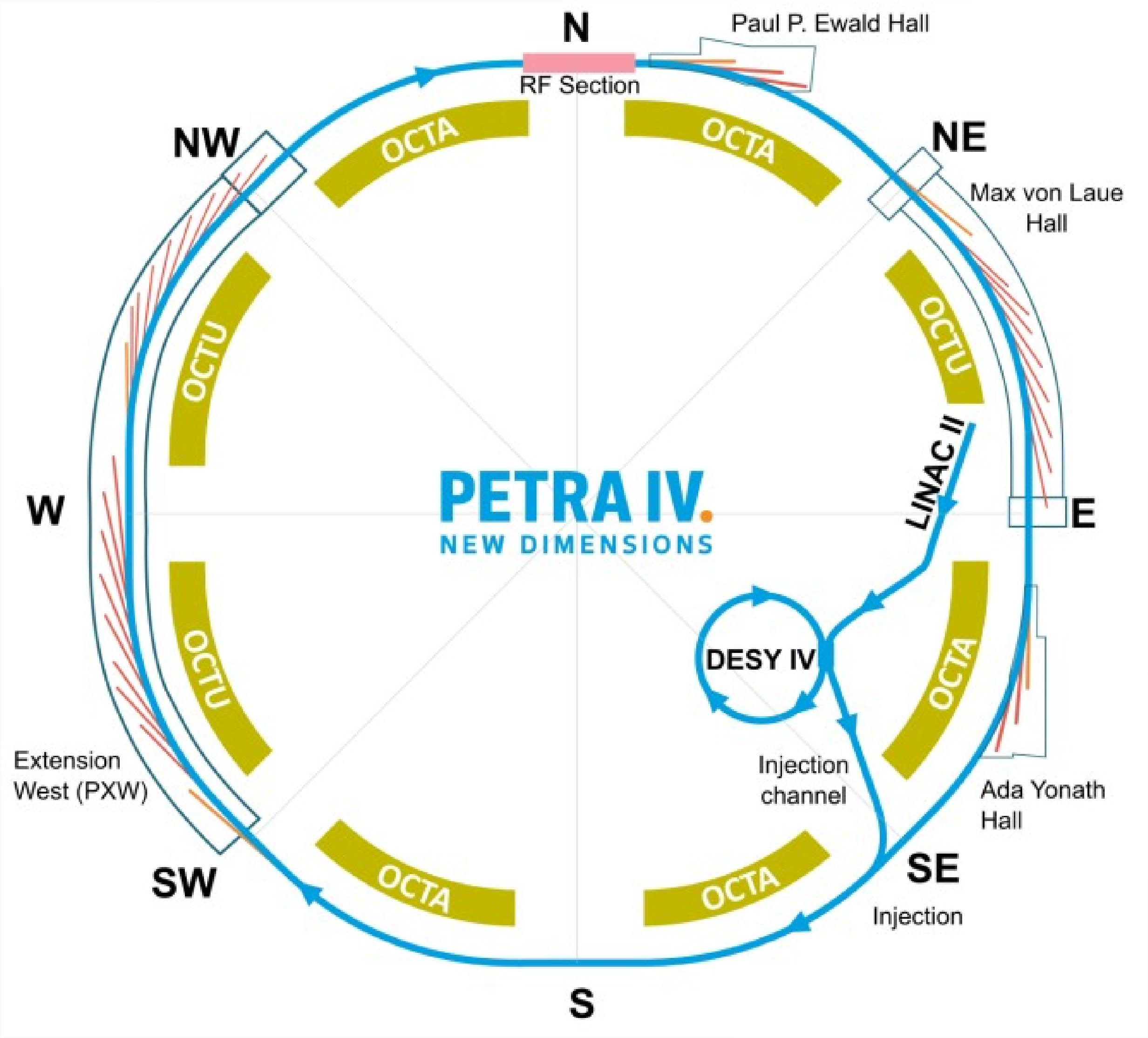
S. A. Antipov

20.06.24

Many thanks I. Agapov, Y.-C. Chae, C. Cortés García, F. Lemery, C. Li, A. Rajabi, I. Zagorodnov

Ultrafast Beams and Applications, Yerevan, Armenia

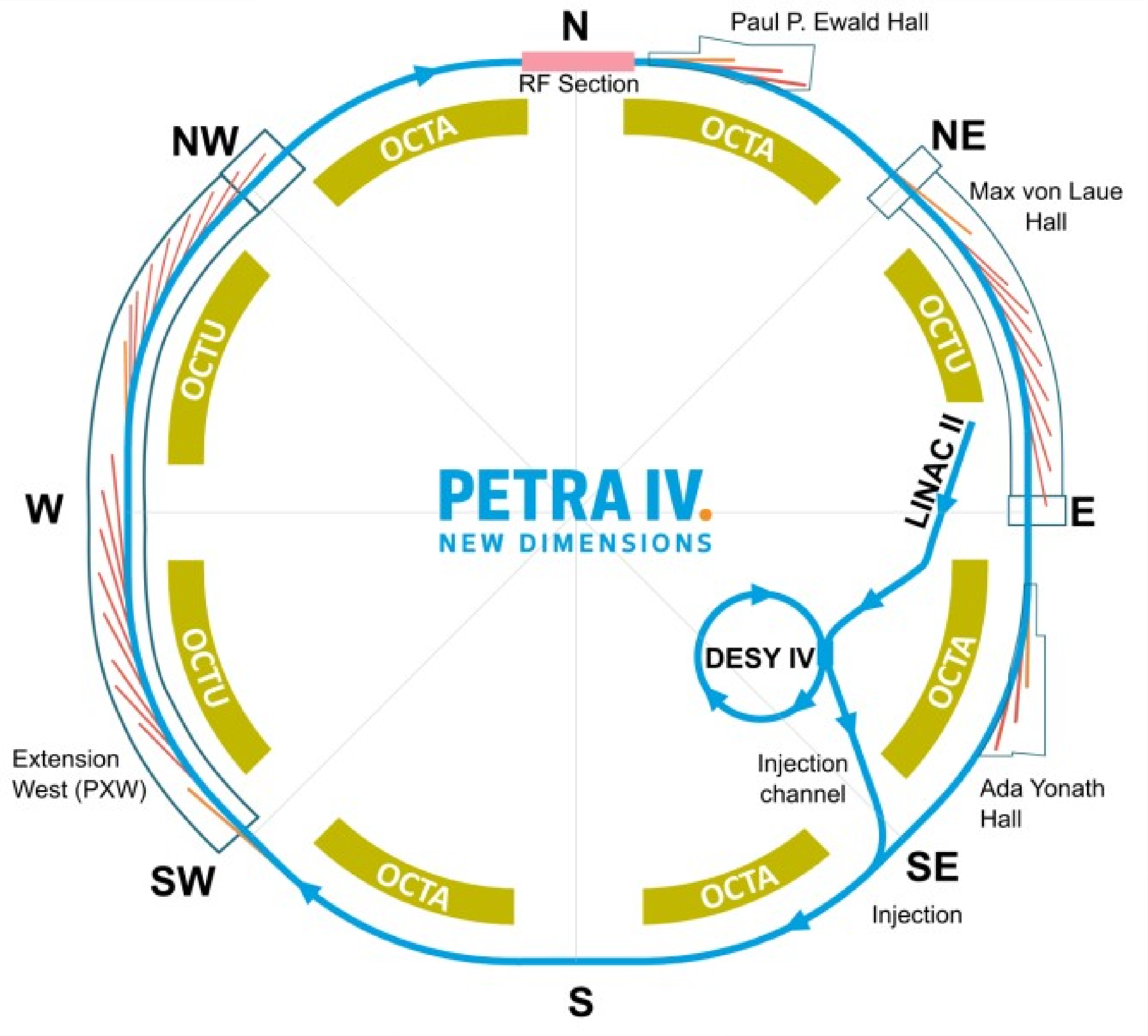
PETRA IV: Germany's future flagship light source



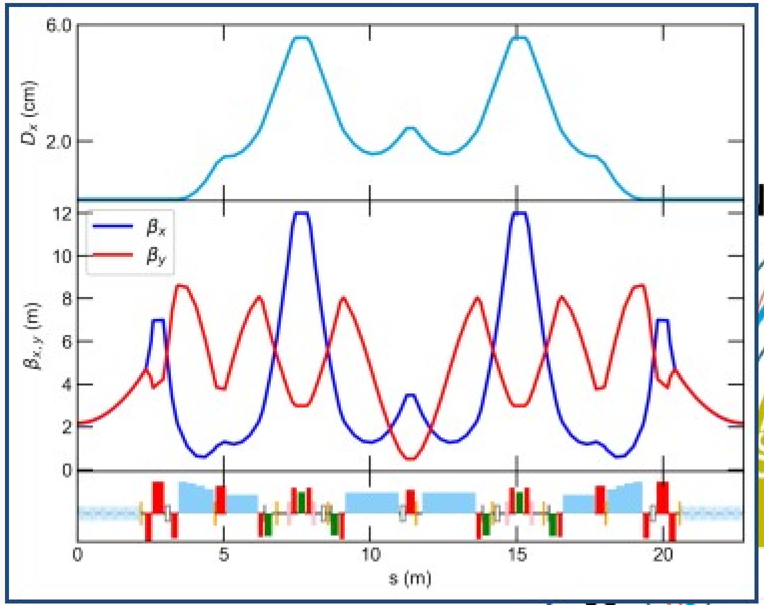
Circumference	2304 m
Energy	6 GeV
Emittance	Hor.: 20 pm, vert.: 2 pm
Diffraction limit	**10 keV**
Coupling	0.2
Energy spread	0.9×10^{-3}
Mom. compaction	3.33×10^{-5}
Nat. bunch length	2.3 mm
Tunes	135.18, 86.27
Energy loss / turn (ID closed)	4.30 MeV
Chromaticity	5, 5
RF voltage (MC)	8 MV
Harmonic number	3840 (500 MHz)
Max. total current	**200 mA**

PETRA IV: Germany's future flagship light source

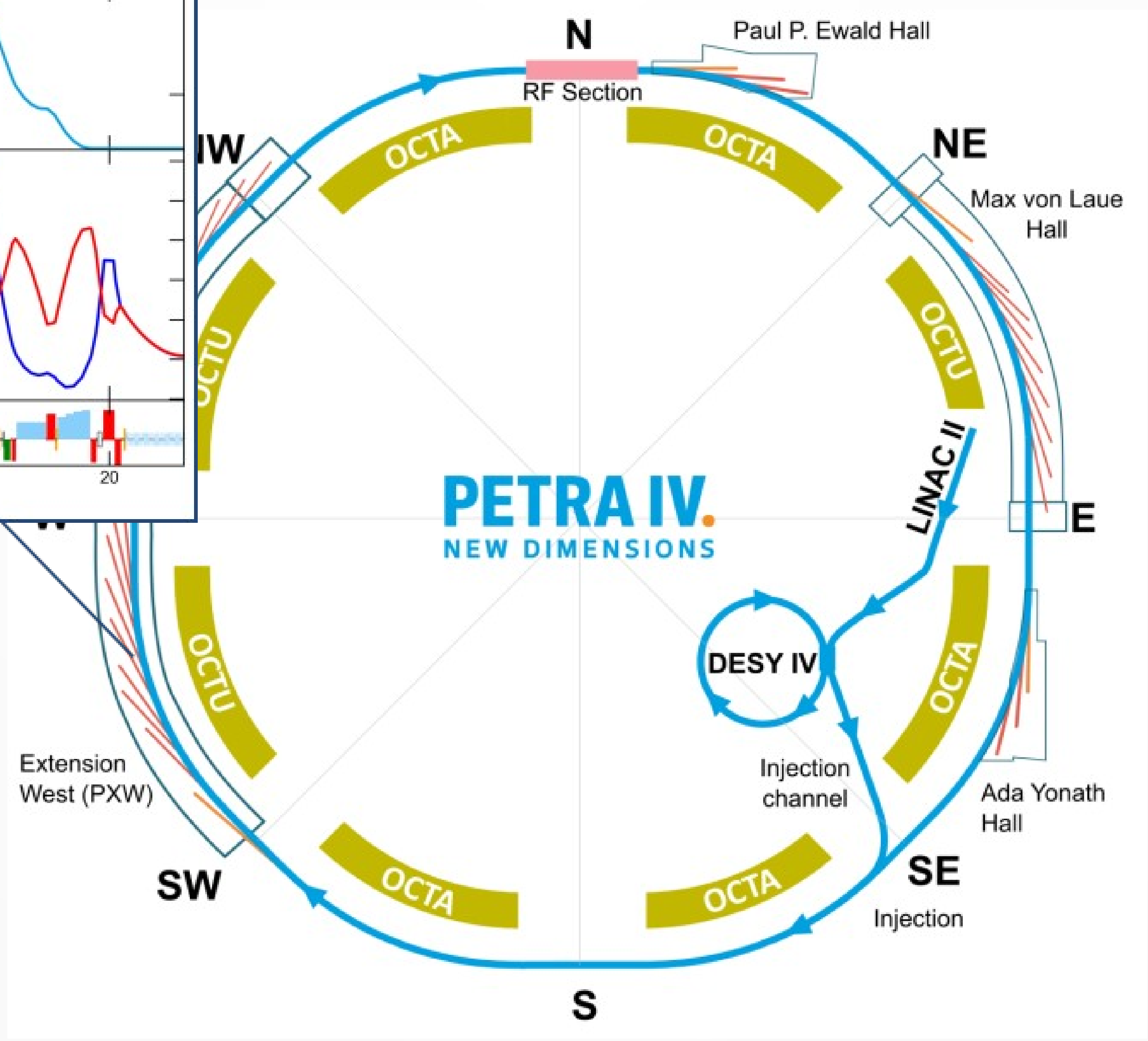
Gluons discovered here in 1979



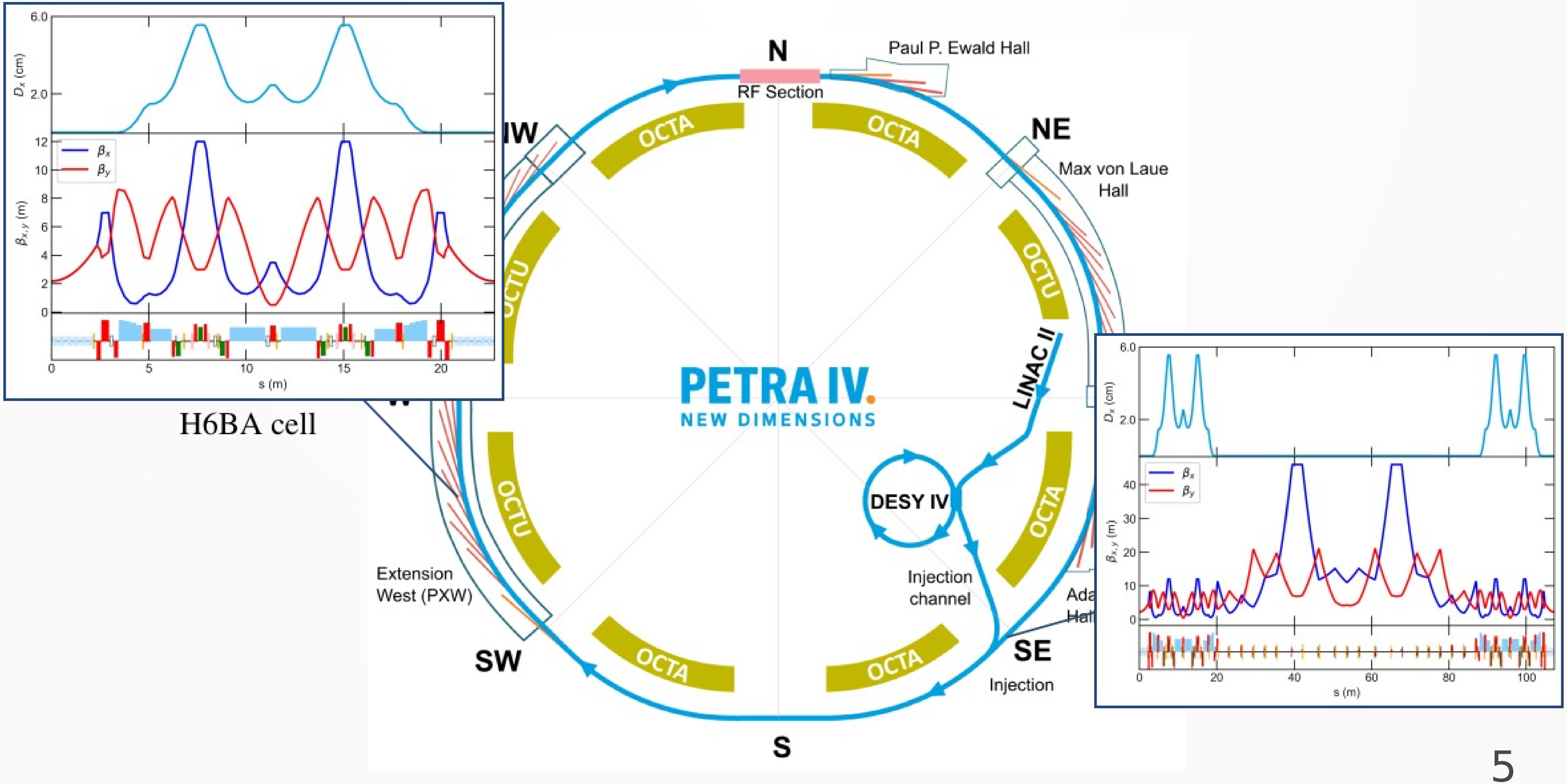
PETRA IV: Germany's future flagship light source



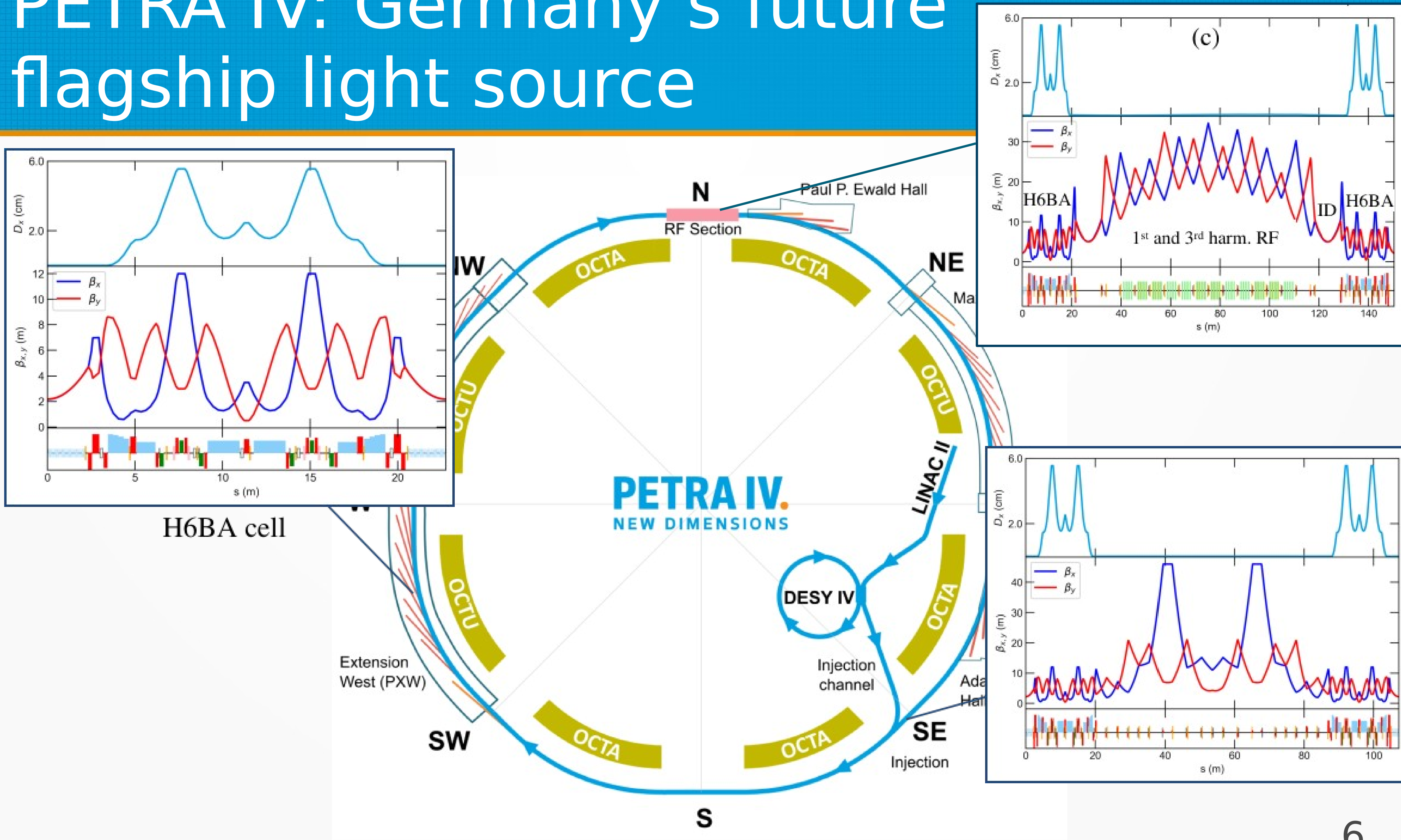
H6BA cell



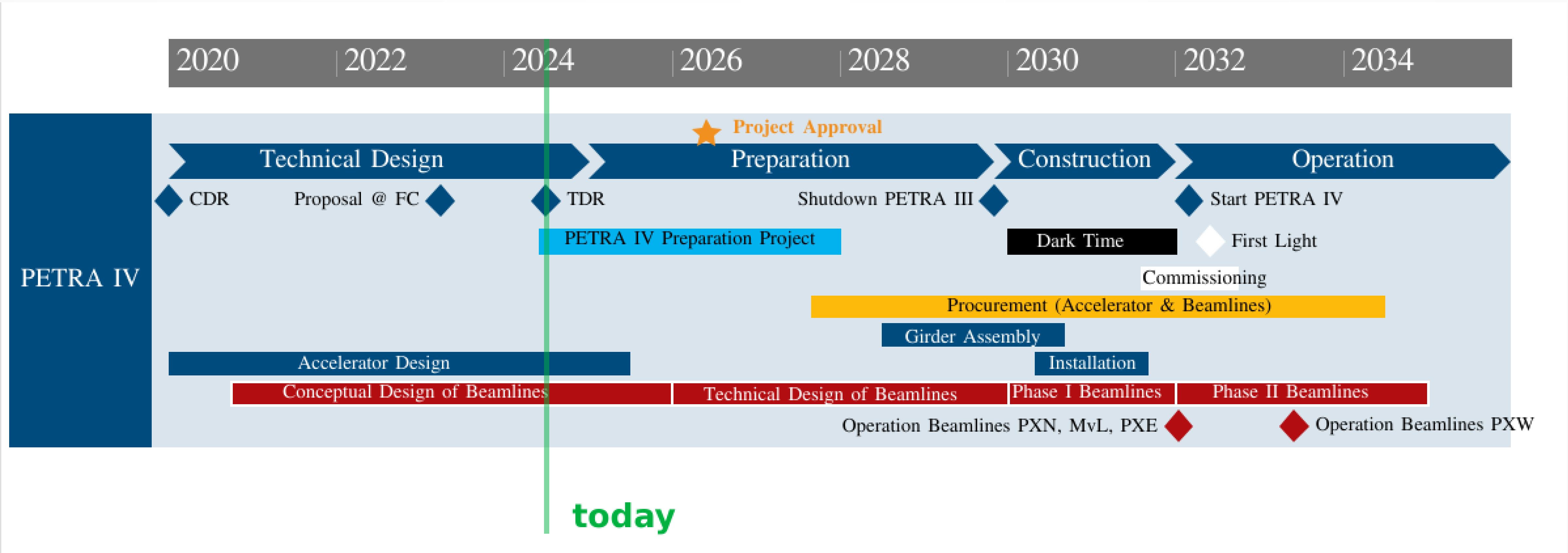
PETRA IV: Germany's future flagship light source



PETRA IV: Germany’s future flagship light source



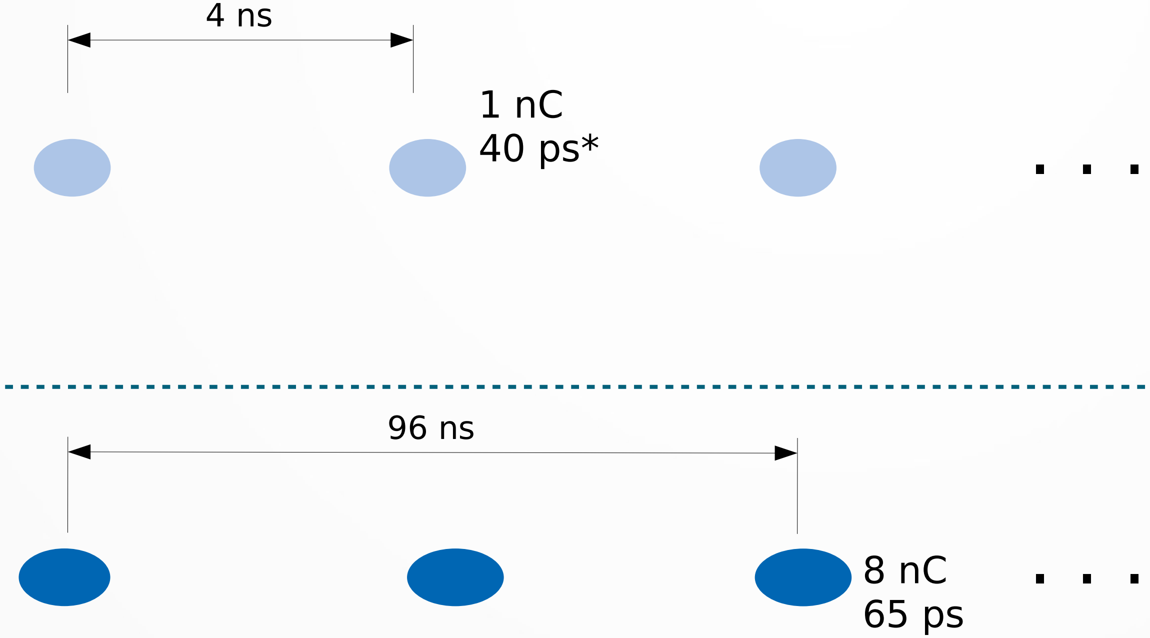
PETRA IV light source: Schedule



Courtesy S. Klumpp,
PETRA IV project support office

Estimated budget: 1.3 BEuro

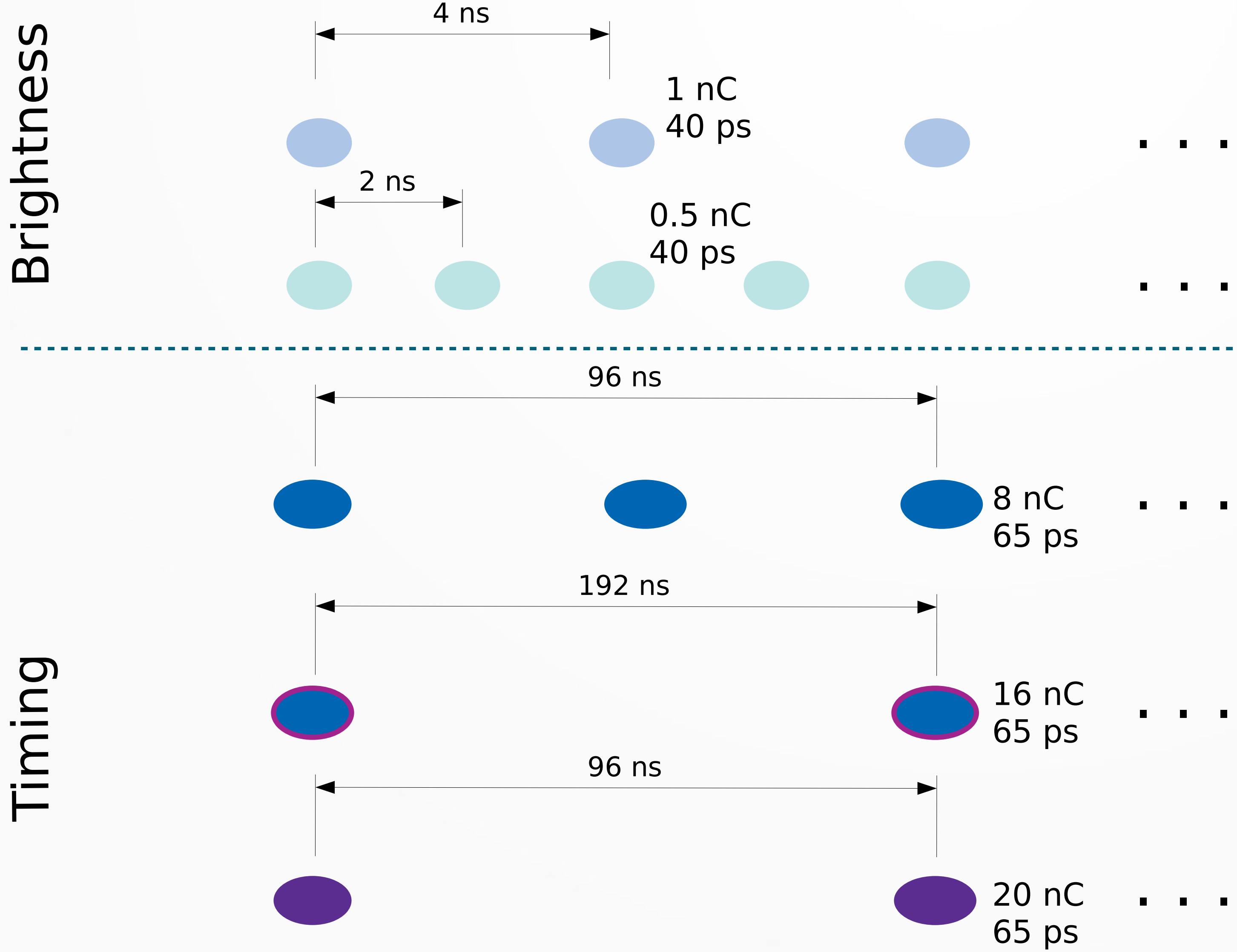
Foreseen filling patterns



	Pattern	Current
Brightness	80 x (20b + 4e) @ 4 ns	200 mA
Timing	80 b @ 96 ns	80 mA

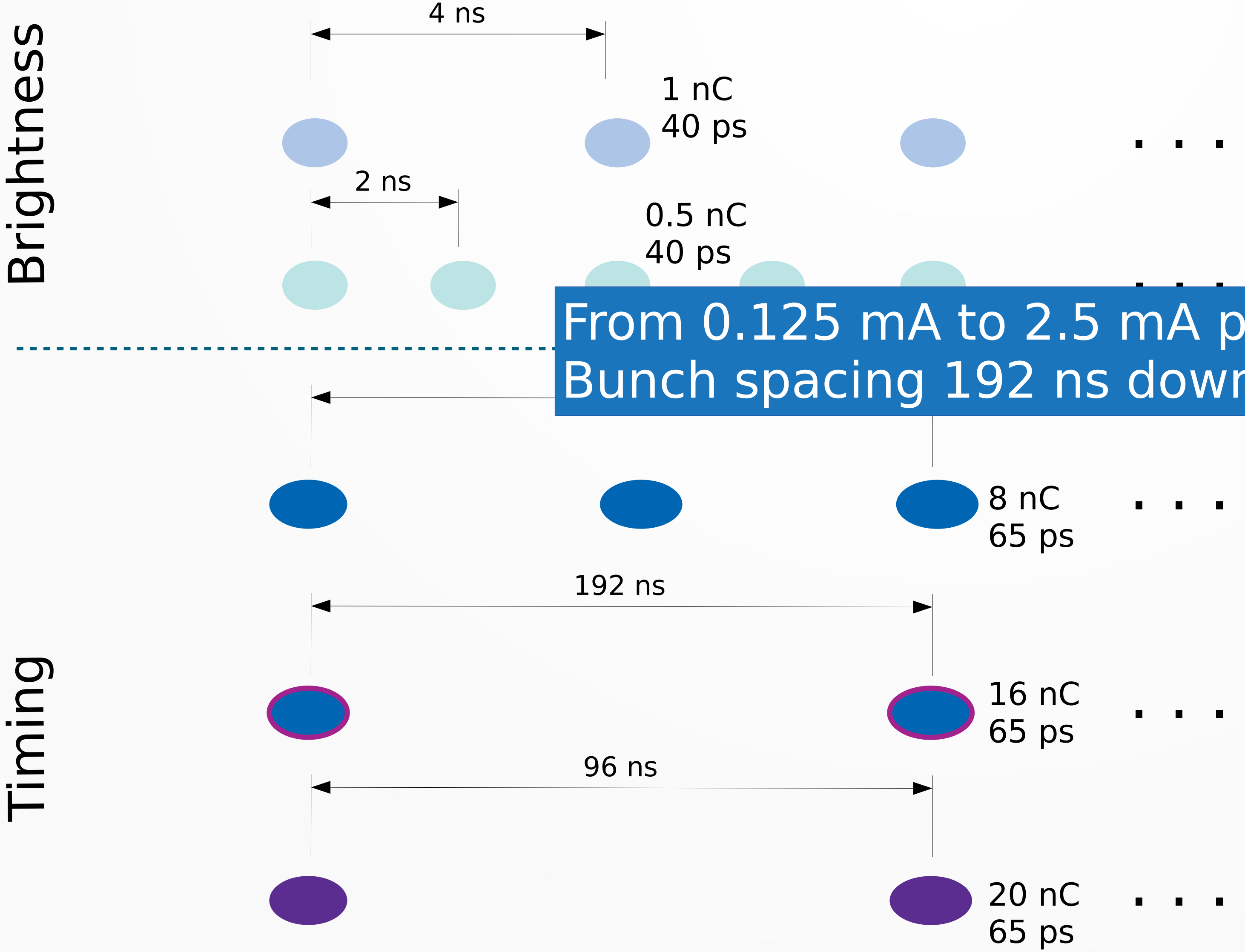
* rms value, includes RF, IBS, Impedance

More exotic filling patterns



Pattern	Current
80 x (20b + 4e) @ 4 ns	200 mA
80 x (40b + 8e) @ 2 ns	200 mA
80 b @ 96 ns	80 mA
40 b @ 192 ns	80 mA
80 b @ 96 ns	200 mA

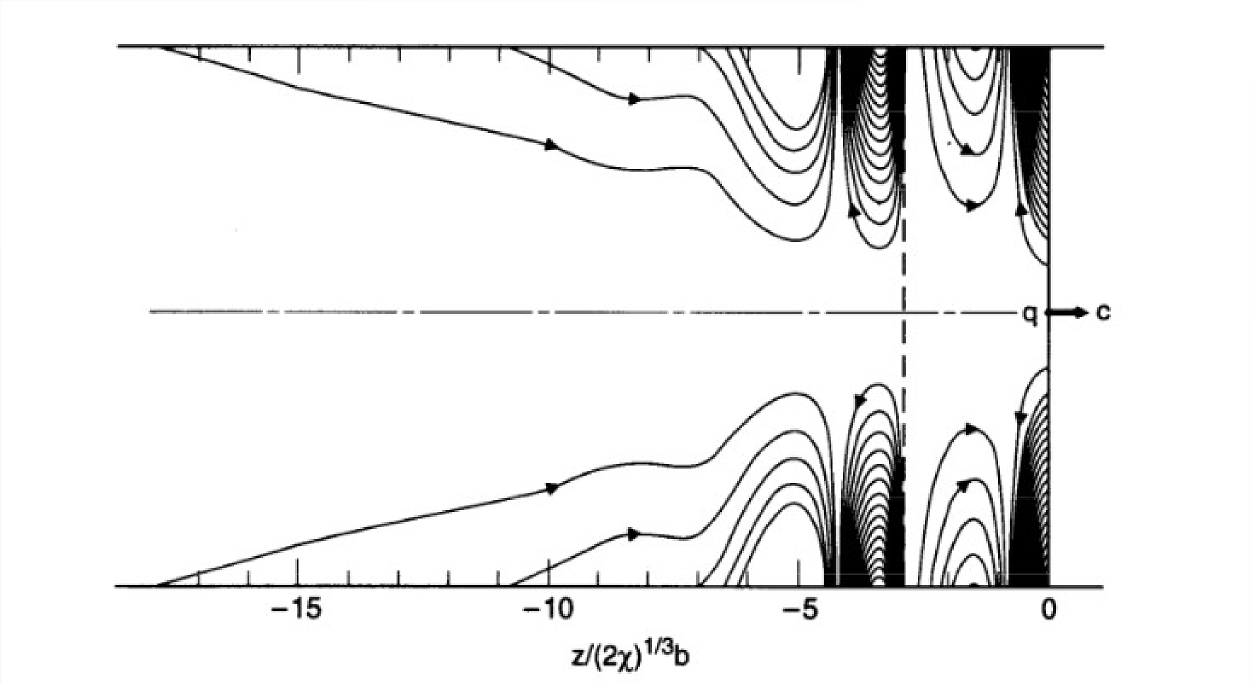
More exotic filling patterns



From 0.125 mA to 2.5 mA per bunch
Bunch spacing 192 ns down to 2 ns

Pattern	Current
80 x (20b + 4e) @ 4 ns	200 mA
80 x (40b + 8e) @ 2 ns	200 mA
80 b @ 96 ns	80 mA
40 b @ 192 ns	80 mA
80 b @ 96 ns	200 mA

Goal: Ensure sufficient stability margin for all modes of operation



A. Chao, *Physics of collecitve beam instabilities in particle accelerators*, Willey 1993

- Need an accurate model of EM wakefields
  - **From 1 kHz** (long-range multi-turn wakes, CB instabilities)
  - **To 0.1 THz** (short-range wakes, microbunching)

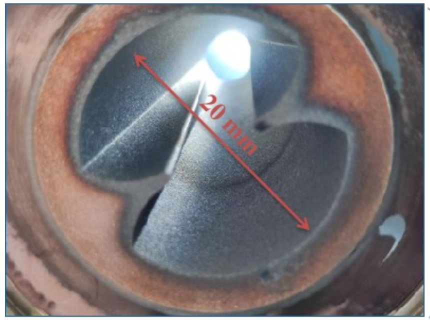
Goal: Ensure sufficient stability margin for all modes of operation

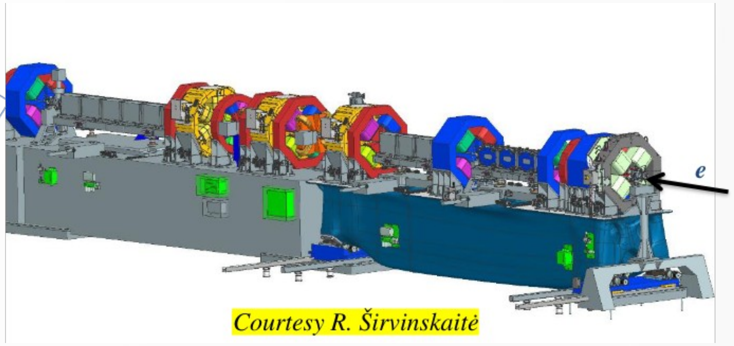
- Main sources of wakefields
  - Resistive wall
  - Higher order modes
  - Beam-ion interaction
- Stabilizing mechanisms
  - Chromaticity (dQ/dp)
  - Active multibunch feedback
  - Synchrotron radiation damping

- Want at least a 100% safety margin at the design stage

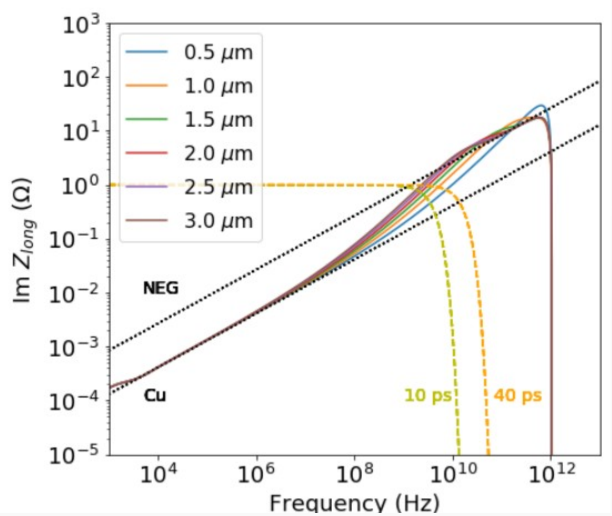
Non-evaporative Getter (NEG) Coating

- Provides distributed pumping as well as desorption barrier
  - More uniform pressure profile
  - Smaller # vacuum pumps needed
  - Simpler machine design
- 1-µm-thick TiZrV and Zr films are being investigated
- Might have a significant effect on the machine impedance
  - Planning to coat all 2.3 km of vacuum chambers



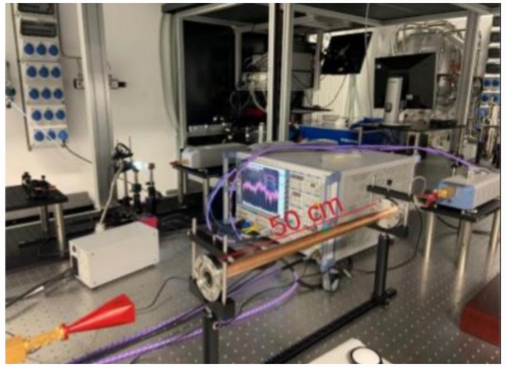


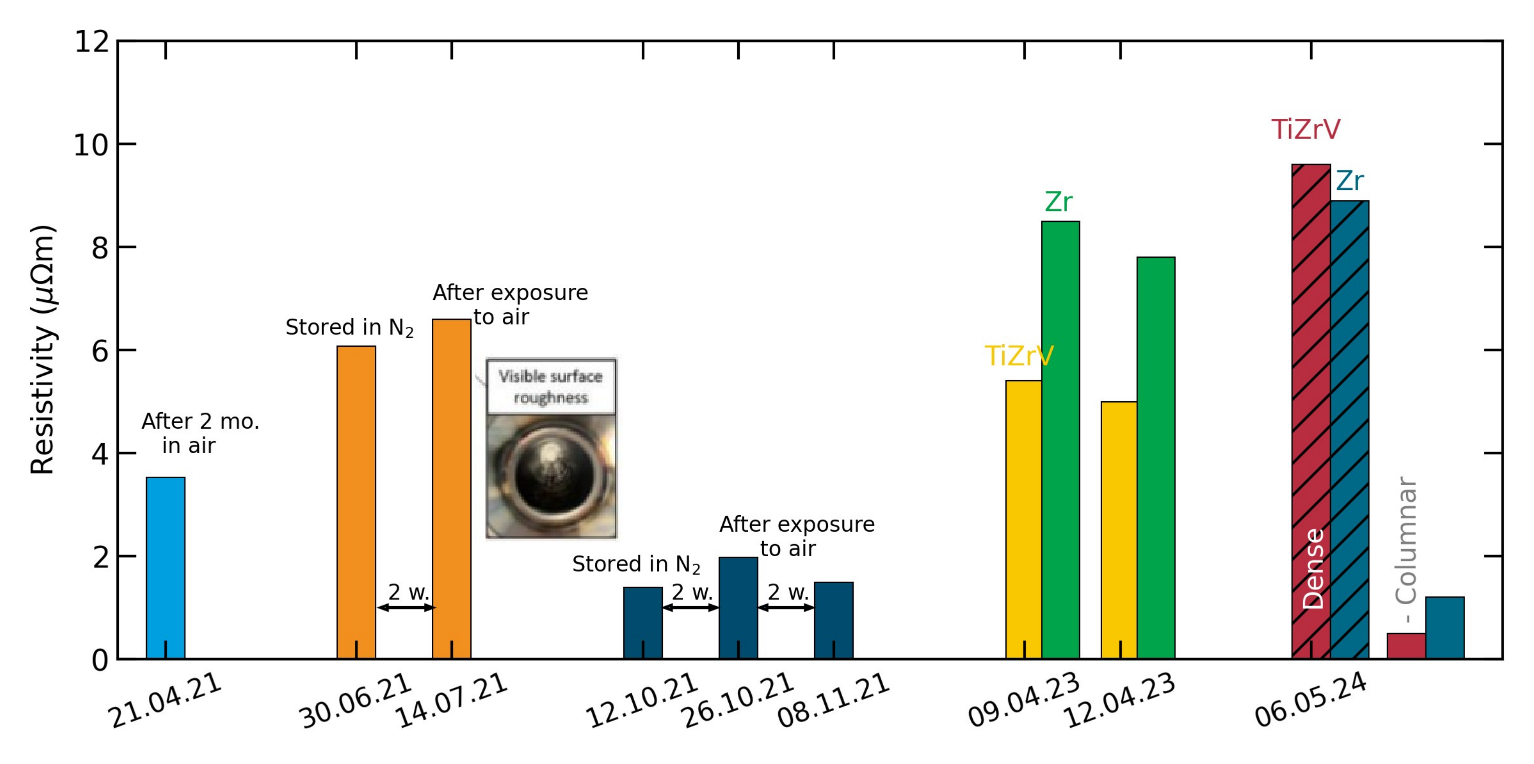
Longitudinal impedance / 1 m
(Simulation in IW2D code)



Investigation of NEG coatings

- EM transmission measurement
  - 75-110 GHz range
  - 50-cm-long samples
  - Round 20 mm diam. Cu pipes

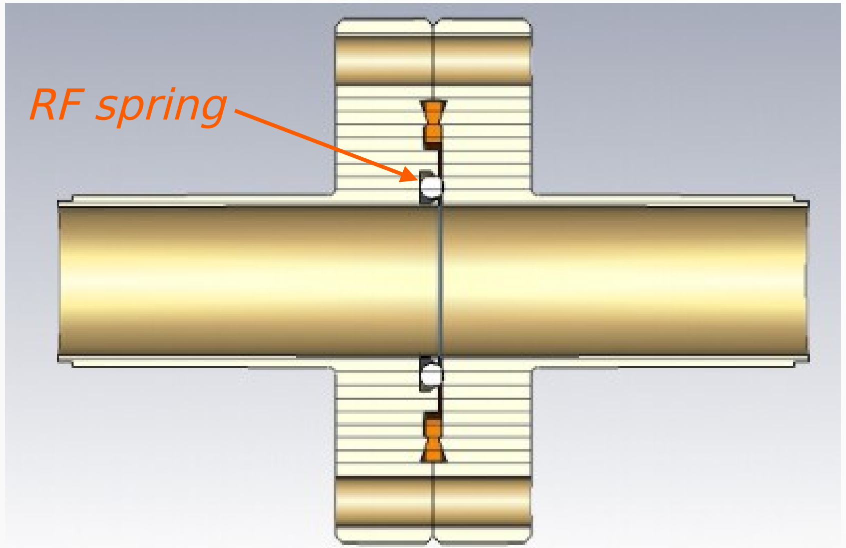




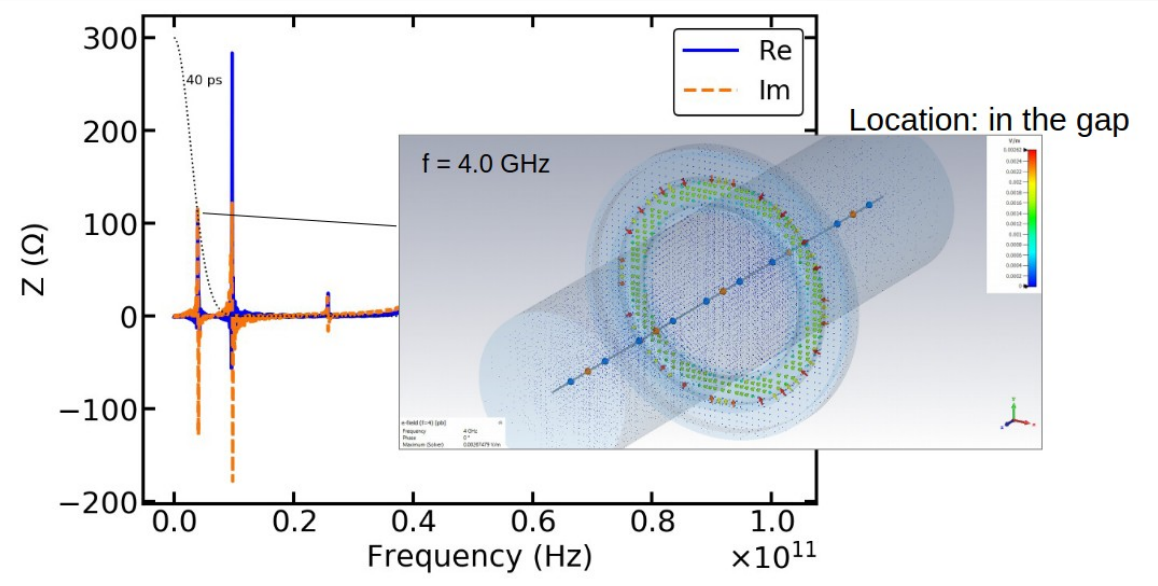
Vacuum flanges

- RF contact is ensured by a special spring

Model in CST Microwave Studio



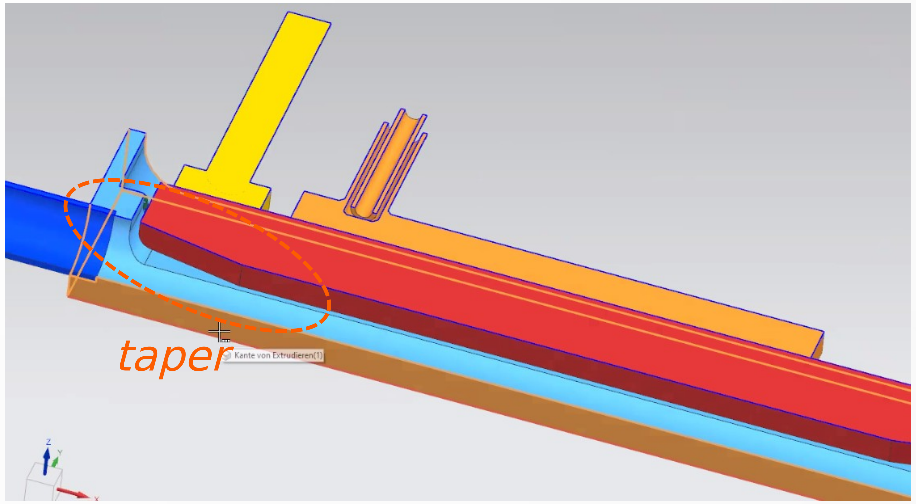
- Additional high frequency modes are trapped in the gap if the RF contact is not perfect
  - 100 µm gap causes problems



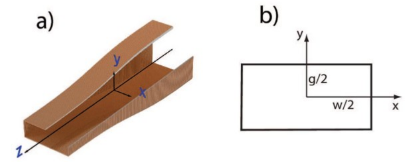
Machine protection collimators

- Horizontal and vertical collimators are installed to
  - Protect the insertion devices
  - Localize the beam (Touschek) losses
- High efficiency = high β-function + small gaps = large impedance
- Mostly geometric contribution from the change in the aperture
  - Need to optimize the tapered transition
- Design studies ongoing
  - Analytical estimates to guide the process
  - Numerical of simplified geometries to verify

Model in CST Microwave Studio



G. Stupakov, PRST AB 10, 094401 (2007)



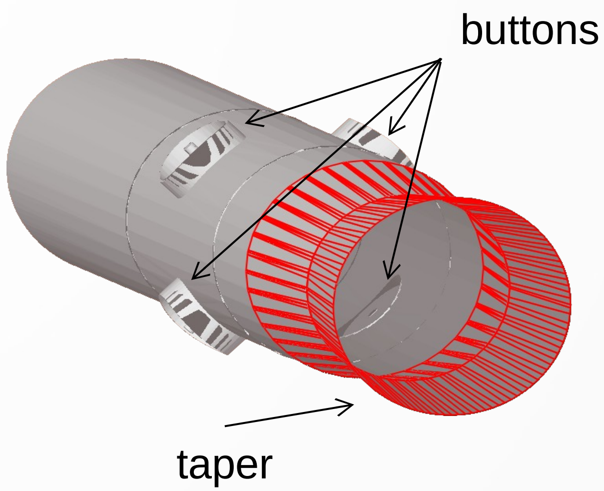
$$Z^{(3)}_{y,d} = -\frac{i\pi w}{c}\int_{-\infty}^{\infty}\frac{(g')^2}{g^3}dz$$

$$Z^{(3)}_{x,d} = Z^{(3)}_{y,q} = -Z^{(3)}_{x,q} = -\frac{i}{c}\int_{-\infty}^{\infty}dz\frac{(g')^2}{g^2}. \quad (76)$$

Beam position monitor shielding

- Synchrotron radiation from bending magnets lands on the monitors
  - Irradiation of the buttons and thermal load
  - Especially problematic at fast corrector locations where SS and CU chambers meet

- Design studies ongoing
  - Analytical estimates to guide the process
  - Numerical of simplified geometries to verify

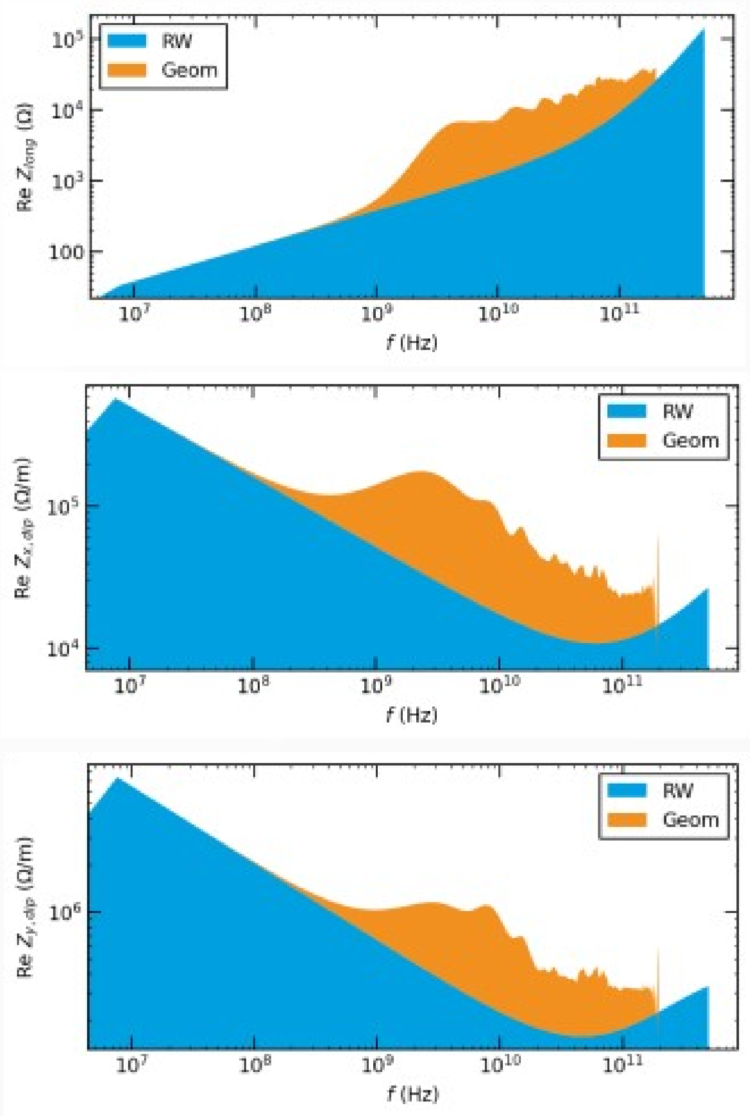


Impedance

- Building the impedance model:
  - Including hardware as it is being designed
  - Geometric impedance simulated up to 100 GHz
- Resistive wall contribution dominates

TABLE III. Impedance contributions at chromaticity 5

Impedance contribution	Value (MΩ/m)	Share (%)
RW round chambers	0.32	23
RW ID chambers	0.64	46
Geometric impedance	≤ 0.4	≤ 30



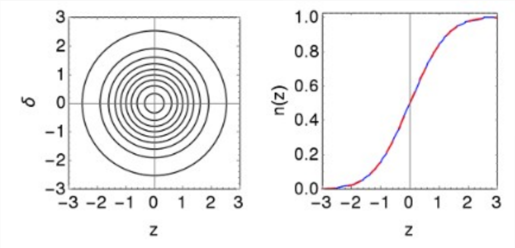
Beam dynamics tools

- NHT Vlasov solver
  - Semi-analytical
  - Fast (laptop)
  - Fixed long. distribution
  - SB + CB problem
  - Idealized linear model
  - SR damping extra

RF well Imp Damp CB

$$\frac{\Delta\omega}{\omega_s} X = \boxed{SX} - \boxed{iZX} - \boxed{igFX} + \boxed{CX},$$

  - Discretized longitudinal distribution



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RF well, Imp, Damp, CB

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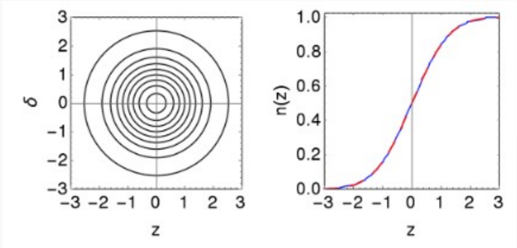
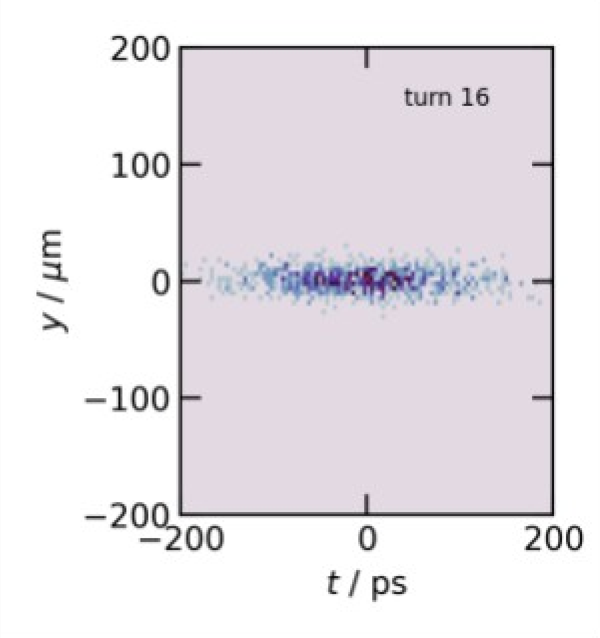


- ELEGANT tracking code
  - Multi-particle (10^5 particles)
  - Slow (computing cluster)
  - Longitudinal + Transverse wakes
  - Single bunch only
  - Errors and aperture
  - SR & QE included

Example instability at high intensity

Leads to blow-up of the transverse beam size in ~1000 turns

Before

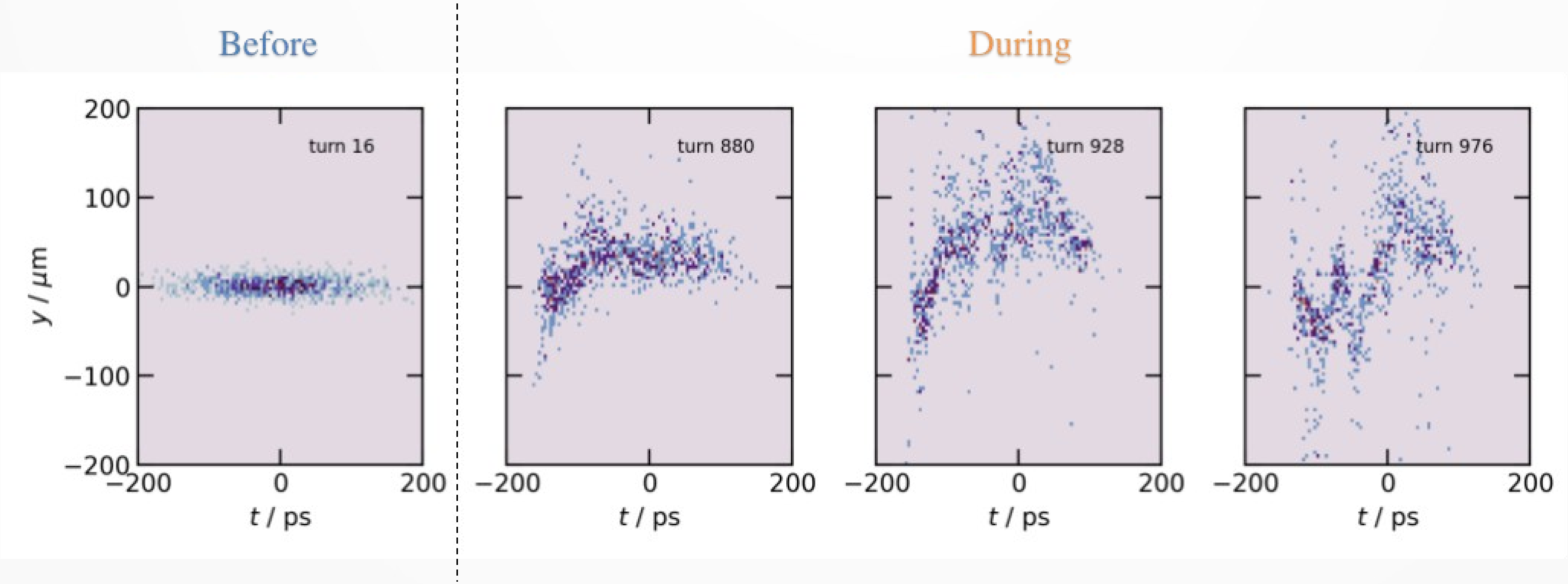


High-charge Timing mode

- 14 nC in the stored bunch
- No apeture sharing (starts from noise)
- Chromaticity 5

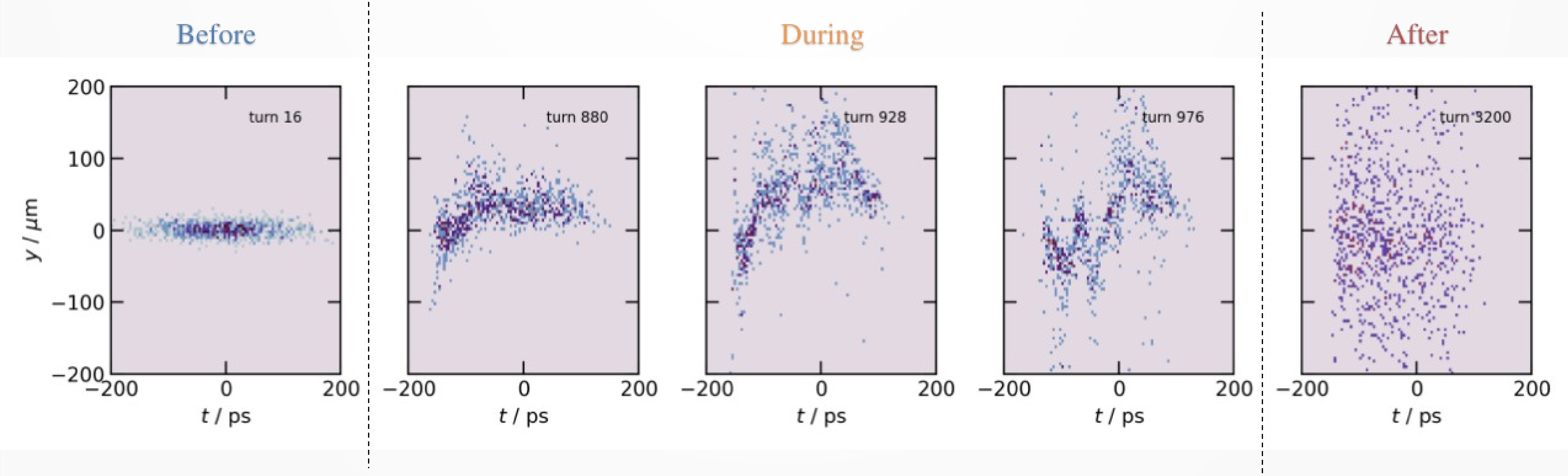
Example instability at high intensity

Leads to blow-up of the transverse beam size in ~1000 turns



Example instability at high intensity

Leads to blow-up of the transverse beam size in ~1000 turns

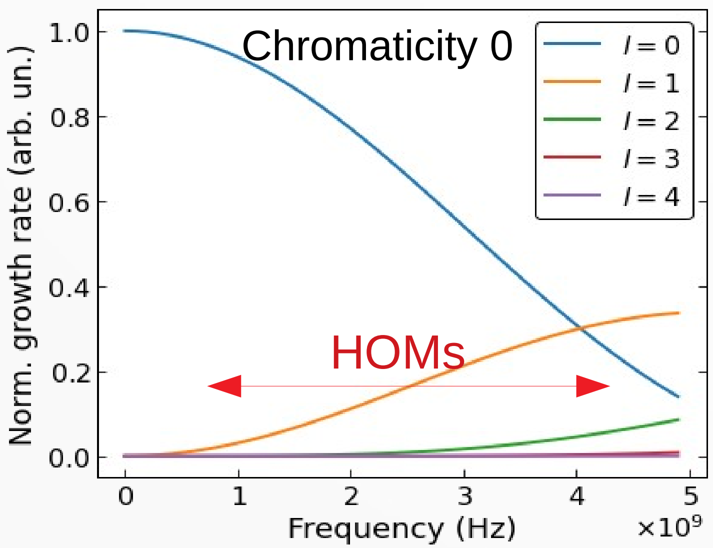


RF straight section: Layout optimized to reduce the β-functions, # aperture transitions

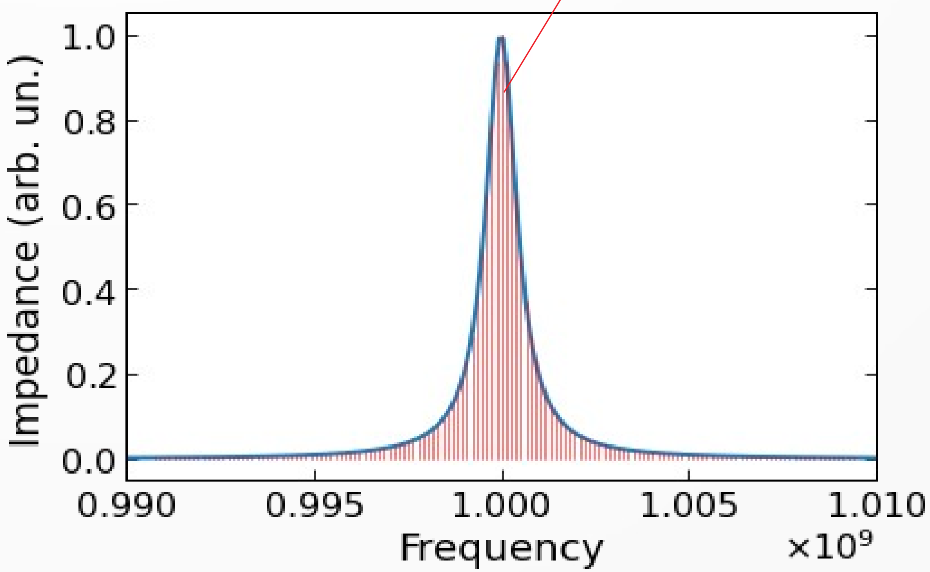
RF straight section: Layout optimized to reduce the β-functions, # aperture transitions

Growth rate — Norm. beam cur. — Impedance — Chromaticity

Low intensity:
$$\Omega^l - \omega_\beta - l\omega_s \sim -i\frac{MN_b r_0 c}{2\gamma T_0^2 \omega_\beta}\sum_p Z(\omega')J_l^2(\omega'\tau - \chi) \qquad \omega' = (pM + \mu)\,\omega_0 + \Omega$$



Not only the dipole (l = 0) head-tail mode excited

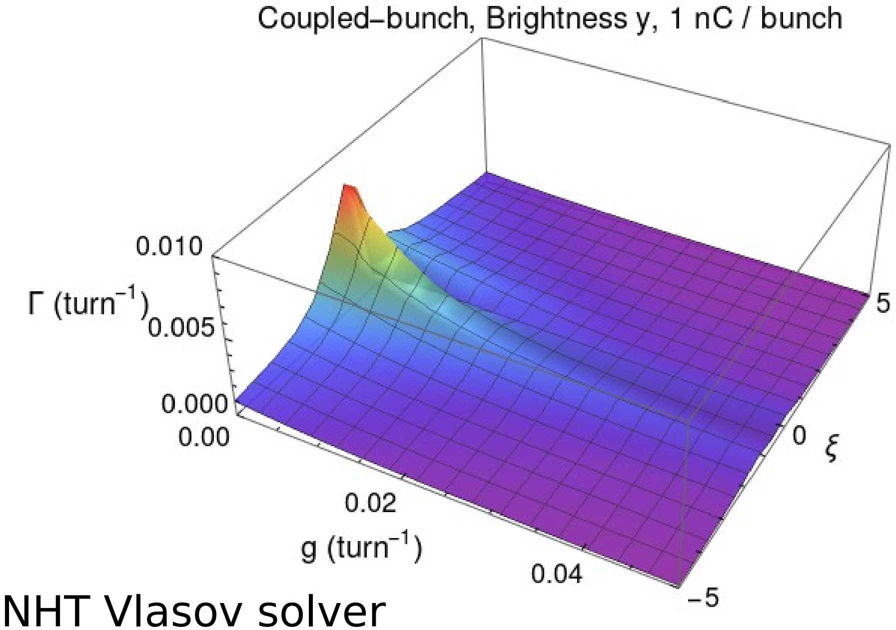


Example: Q = 1000 HOM at 1 GHz

Example: HOM at 1 GHz

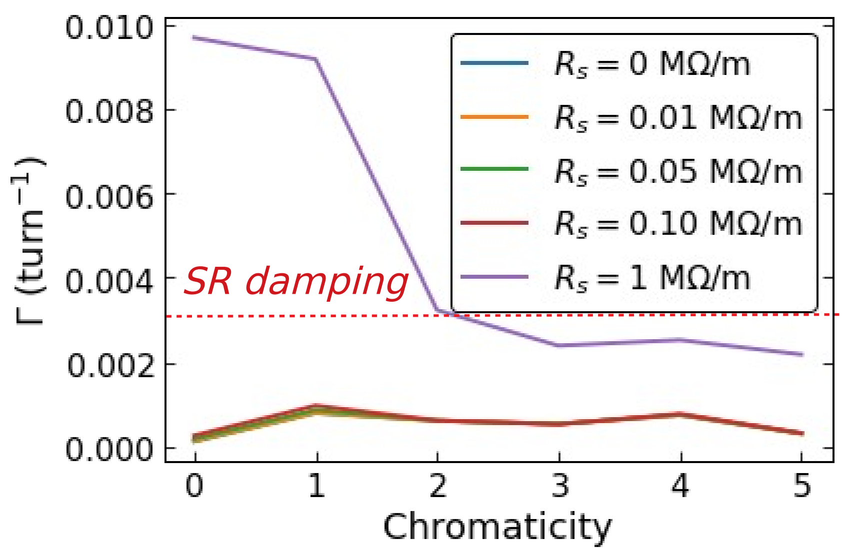
- 24 cavities, β = 20 m, vertical plane, 1920 bunches, Q_b = 1 nC
- Feedback and chromaticity might be insufficient to stabilize

R_s = 1 MΩ/m, no other source of impedance



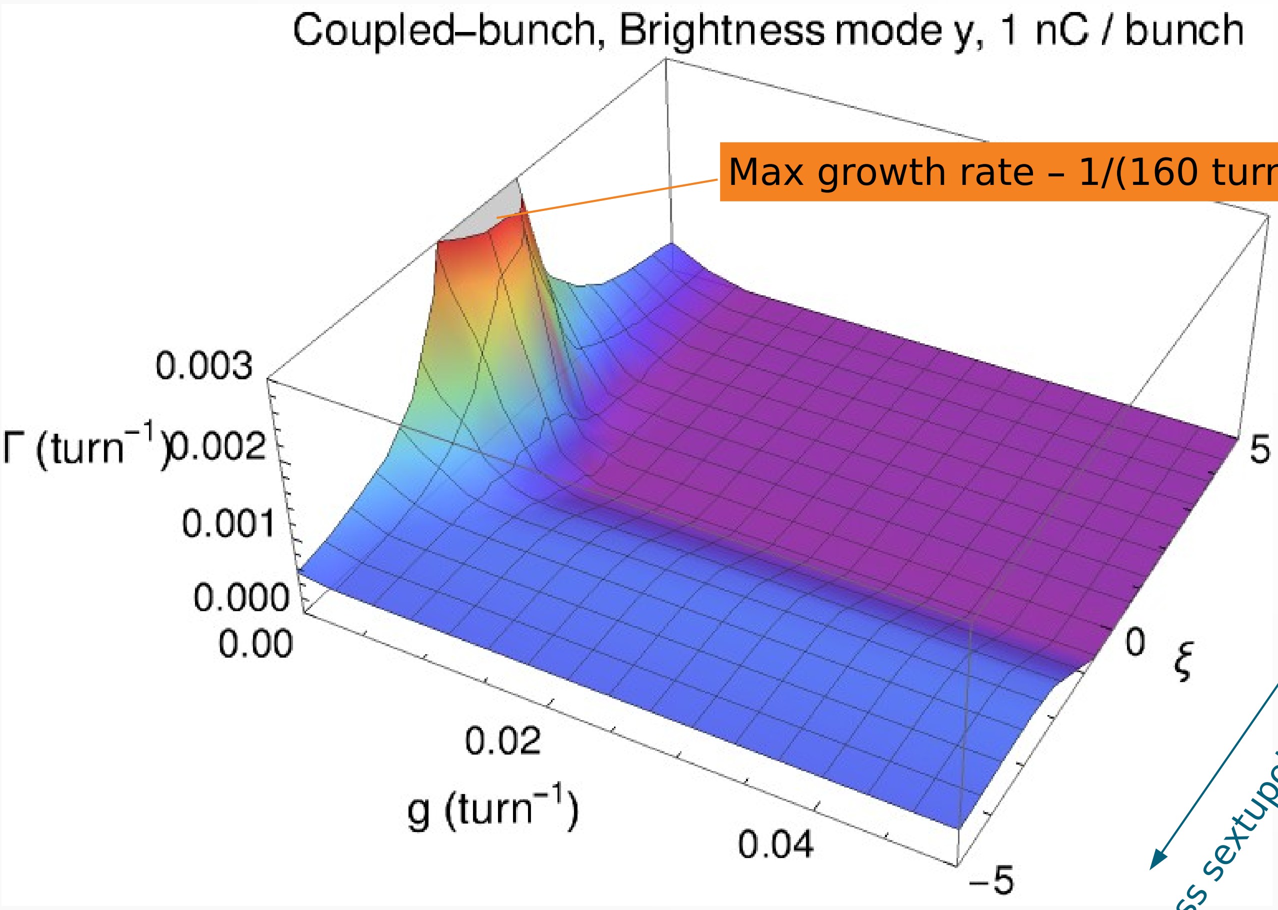
NHT Vlasov solver

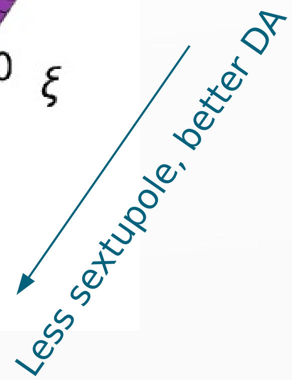
With FB and chroma, full impedance model

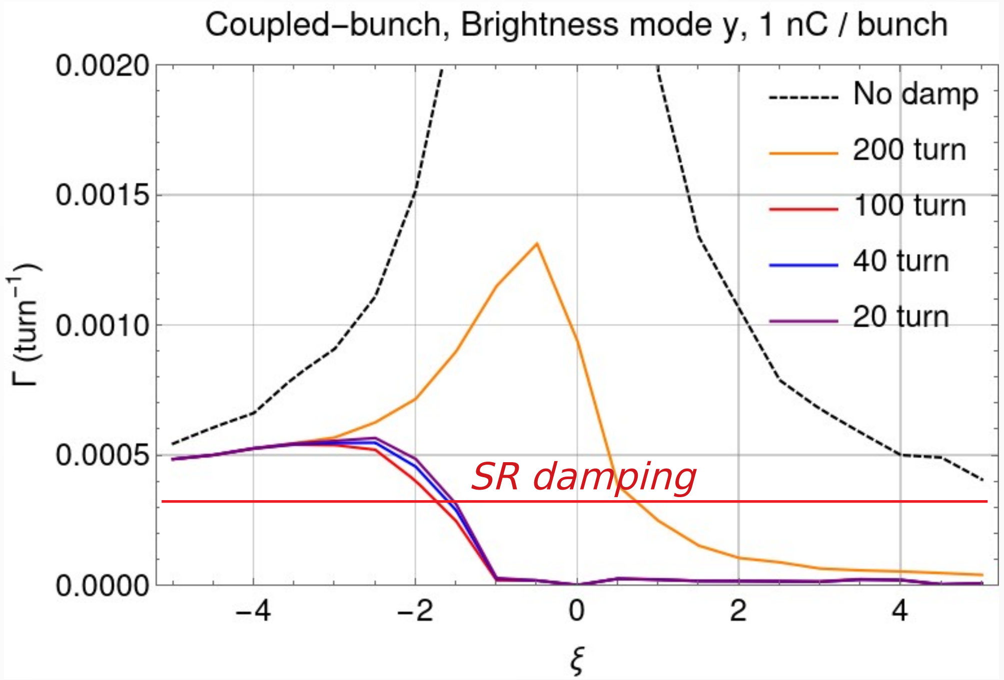


Must make sure the modes are well damped

Brightness mode: Vertical plane

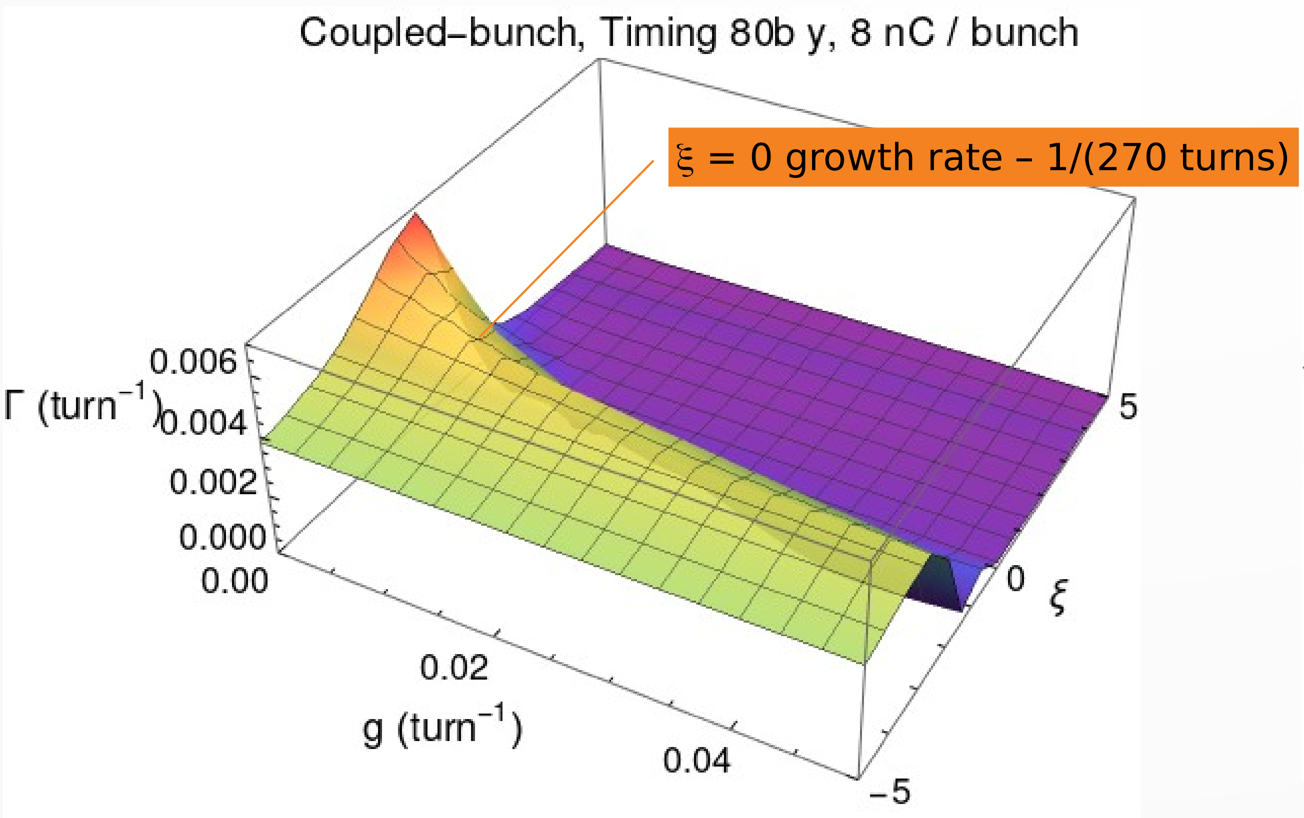


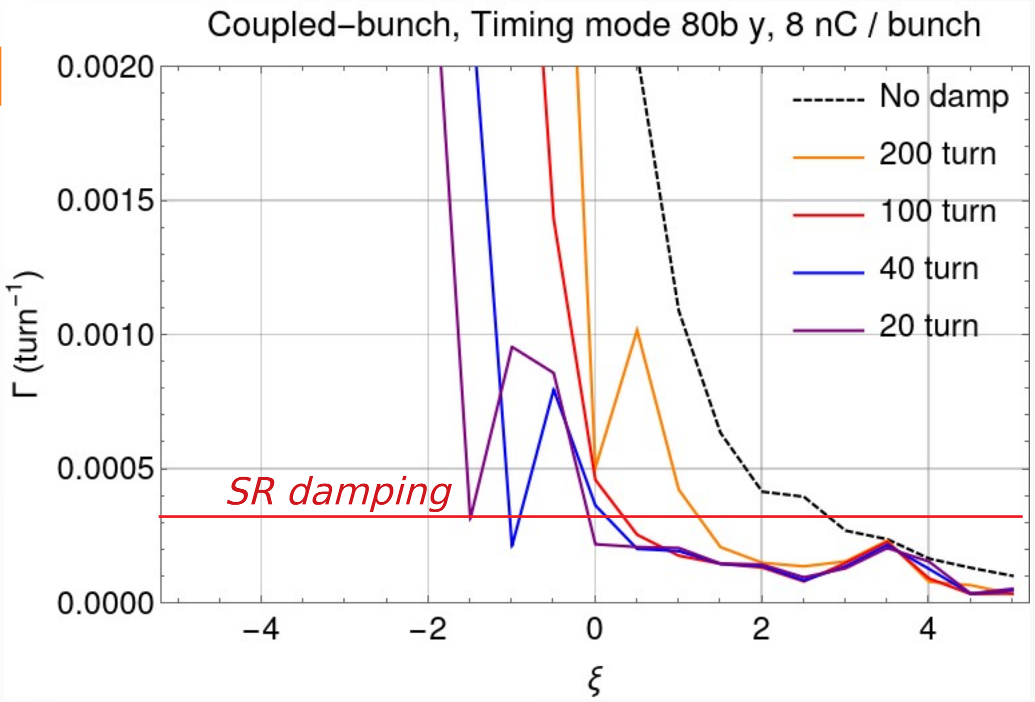




 Transverse feedback is essential for the feasibility of the 200 mA Brightness mode

Timing mode: Vertical plane





Injection dynamics

PAUL SCHERRER INSTITUT PSI

Where are we going?

Kicker-bump injection	Multipole/Nonlinear kicker	Swap-out	Short pulse kicker (Aperture sharing, Long. Inj.)
			
Most 3GLS ESRF-EBS ELETTRA II etc.	MAX IV Sirius Soleil II etc.	ALS-U APS-U HEPS etc.	SLS 2.0 Diamond II PETRA IV etc.

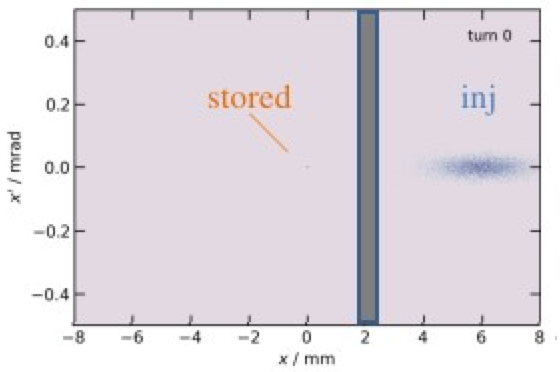
The optimum injection scheme may depend on each storage ring as well as the demands of the beamline users

* Free images from pixabay.com

M. Aiba, "A Review on Injection Schemes", FLS'23, Lucerne, 2023

Injected beam decoheres in several revolutions

No perturbation of the stored bunch observed

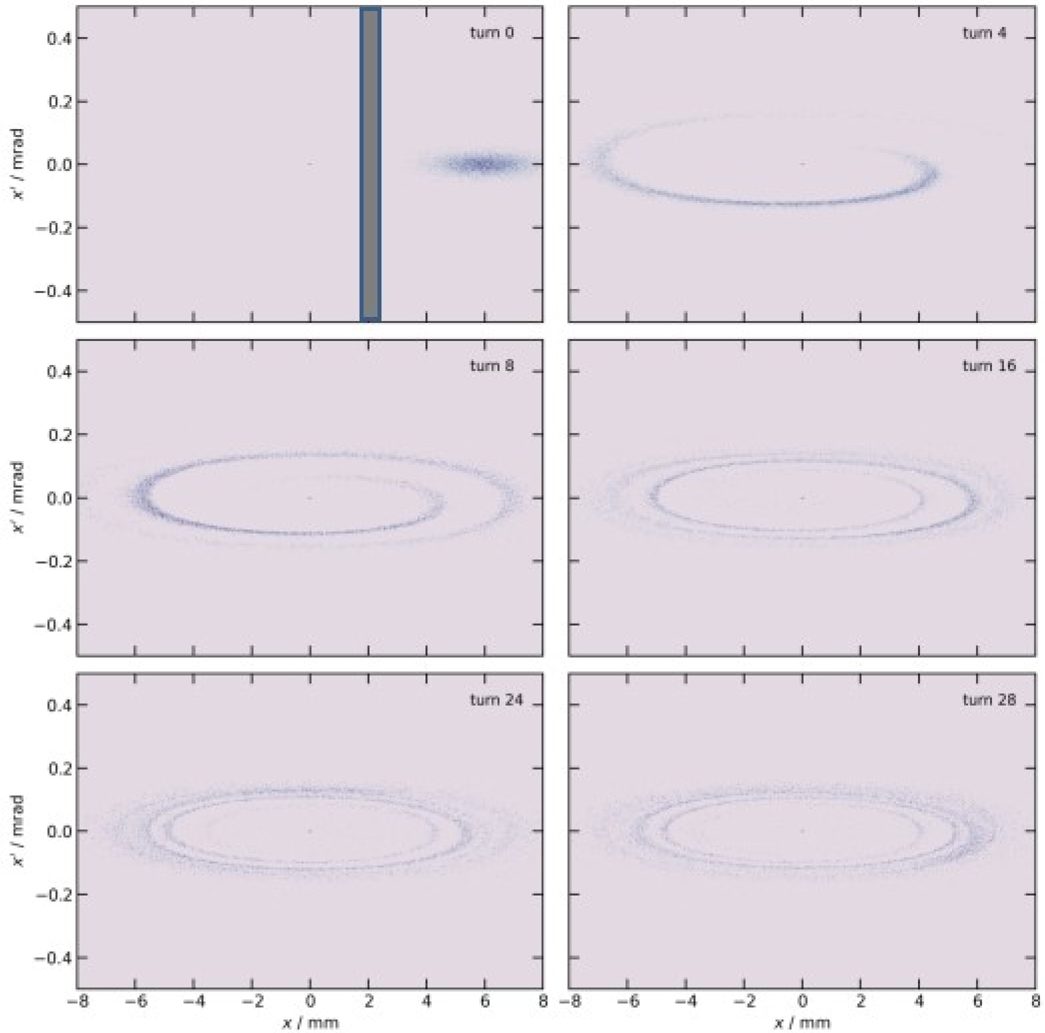


Timing mode example

- 8 nC in the stored bunch: 20, 2 pm
- 800 pC in the injected bunch: 20, 2 nm

Injected beam decoheres in several revolutions

No perturbation of the stored bunch observed



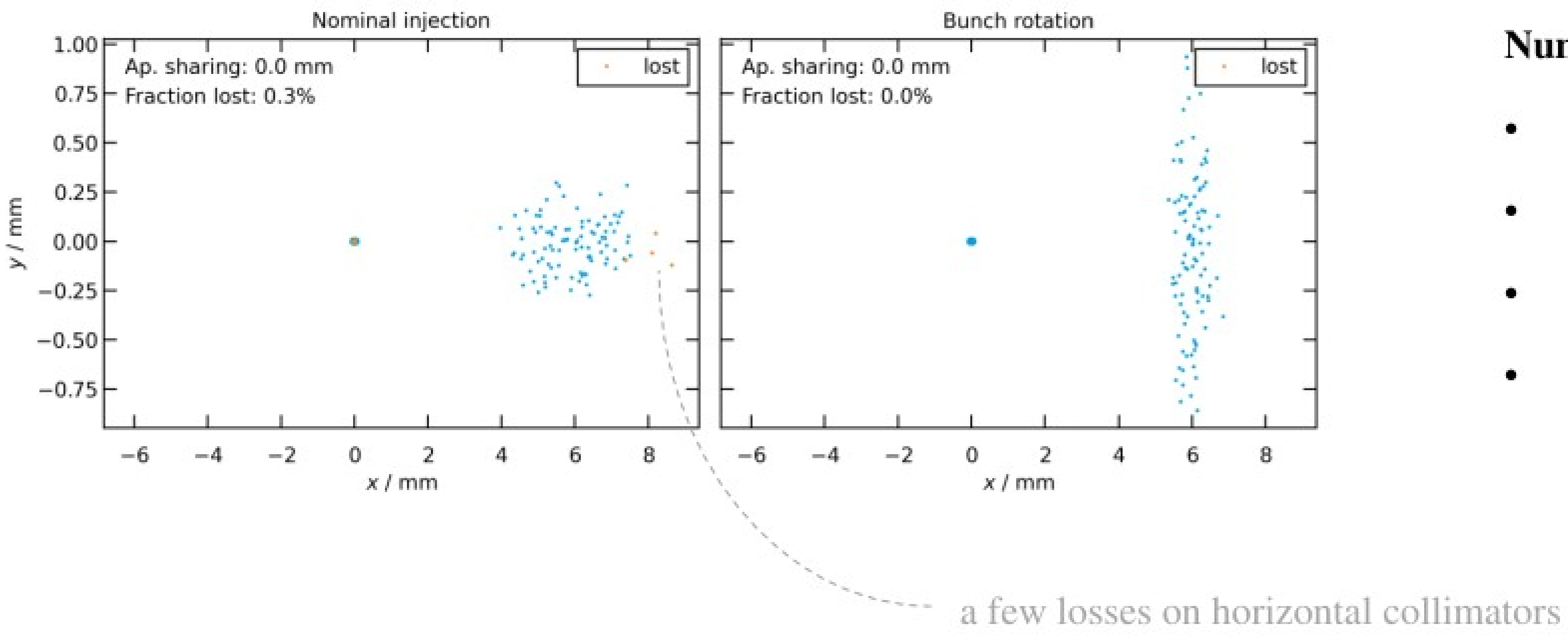
Timing mode example

- 8 nC in the stored bunch: 20, 2 pm
- 800 pC in the injected bunch: 20, 2 nm

Losses mostly happen in the stored beam

Can simulate 1 beam instead of 2

→ Y.-C. Chae, IPAC'07



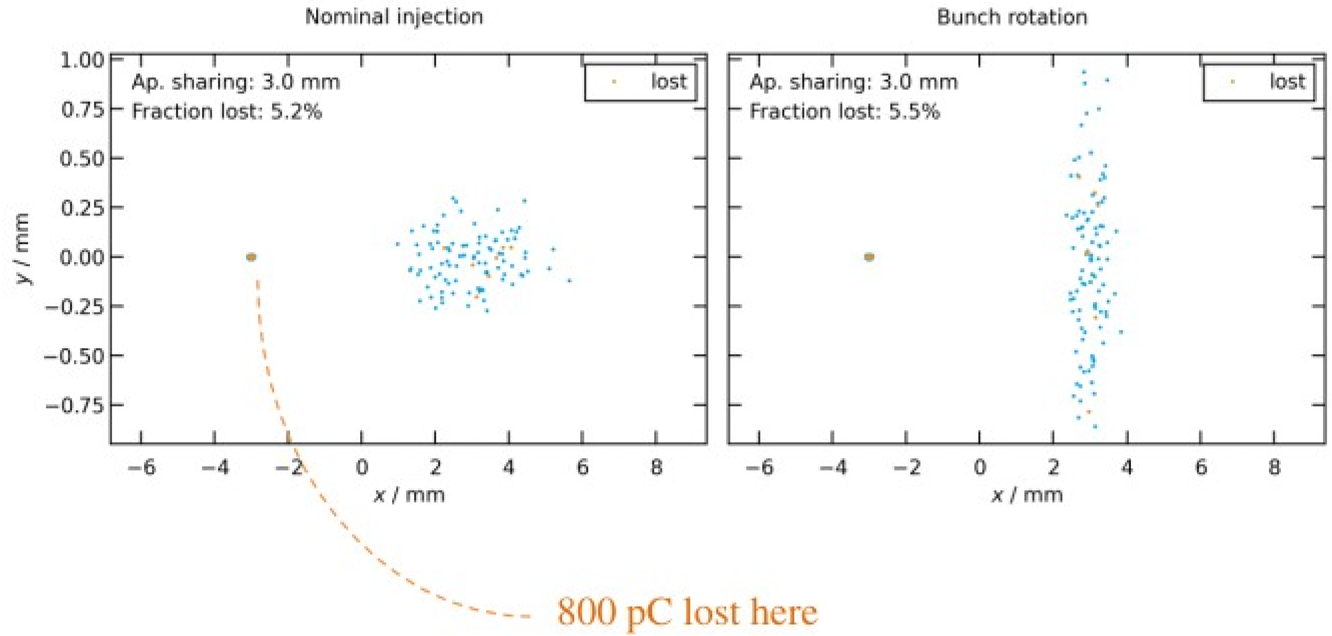
Numerical example:

- 16 nC in the stored bunch
- 800 pC in the injected bunch
- Beam separation 6 mm
- 200 000 macroparticles

Losses mostly happen in the stored beam

Can simulate 1 beam instead of 2

→ Y.-C. Chae, IPAC'07

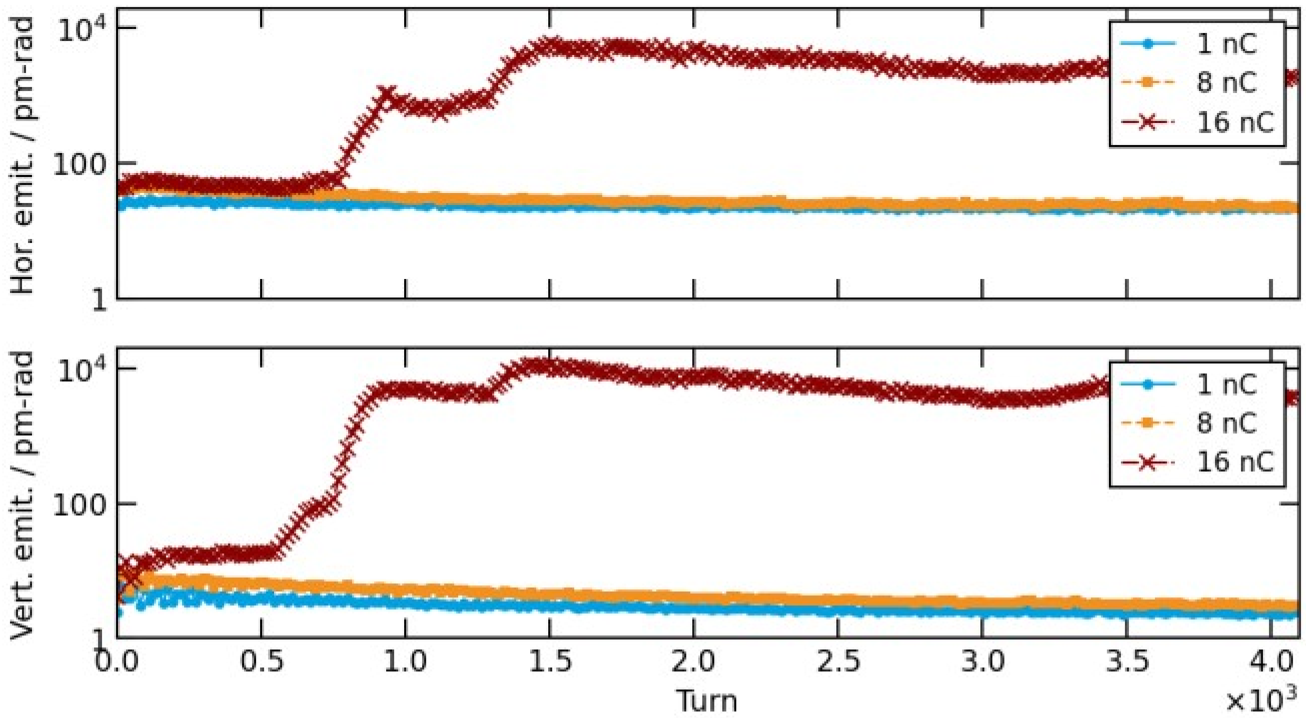


Numerical example:

- 16 nC in the stored bunch
- 800 pC in the injected bunch
- Beam separation 6 mm
- 200 000 macroparticles

Emittance might blow up to nm scale for high charge modes

Blow-up happens on time scales of ~1000 turns

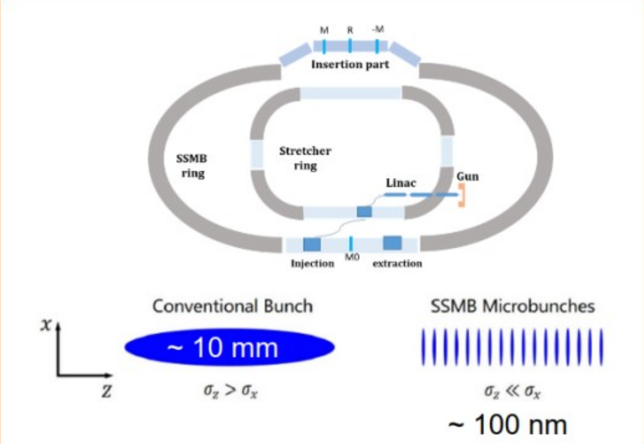


- Chromaticity 5
- Multi-bunch FB not included

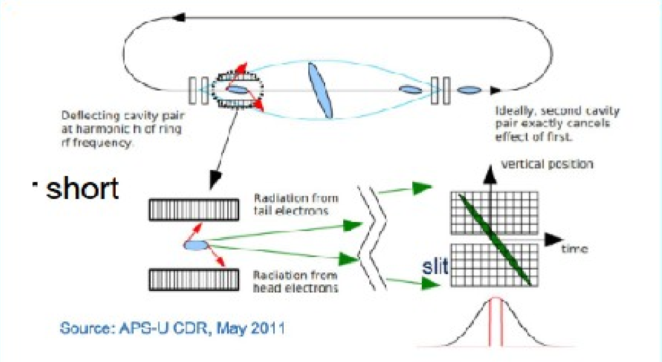
Impedance and stability summary

- Baseline scenarios are stable when using both feedback and chromaticity
  - Gain of ~1/100 turns seems to be sufficient with significant safety margin
  - Beam can be stabilized at 0 chromaticity – beneficial for machine studies
- To guarantee transverse stability HOMs shall be damped below 55 kΩ/m
  - Otherwise, need to be carefully examined separately
- Ongoing work:
  - Refining the impedance model as the hardware is being designed
  - Iterating specifications on feedback controls

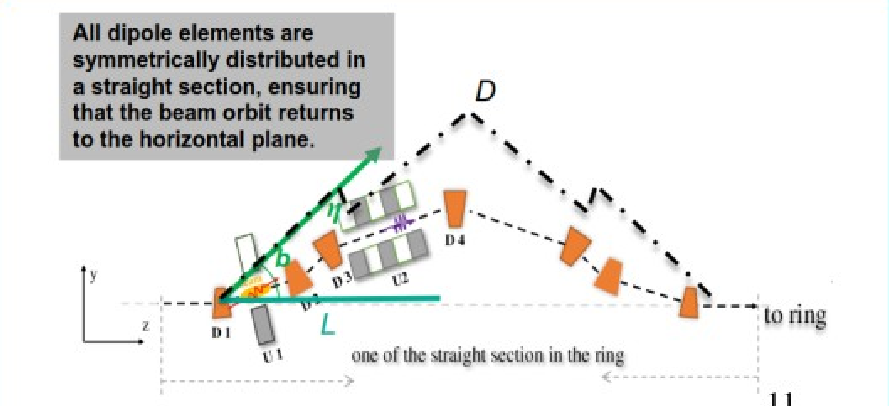
Community-wide interest in concepts to produce short bunches in rings



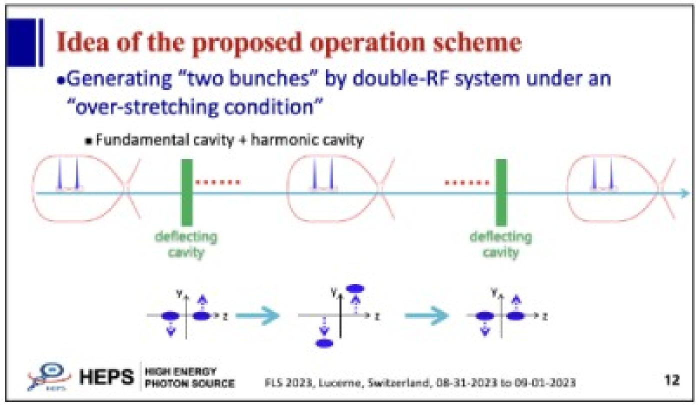
Z. Pan, Low-alpha SR design for SSMB



Crab cavity scheme, X. Huang (SLAC)



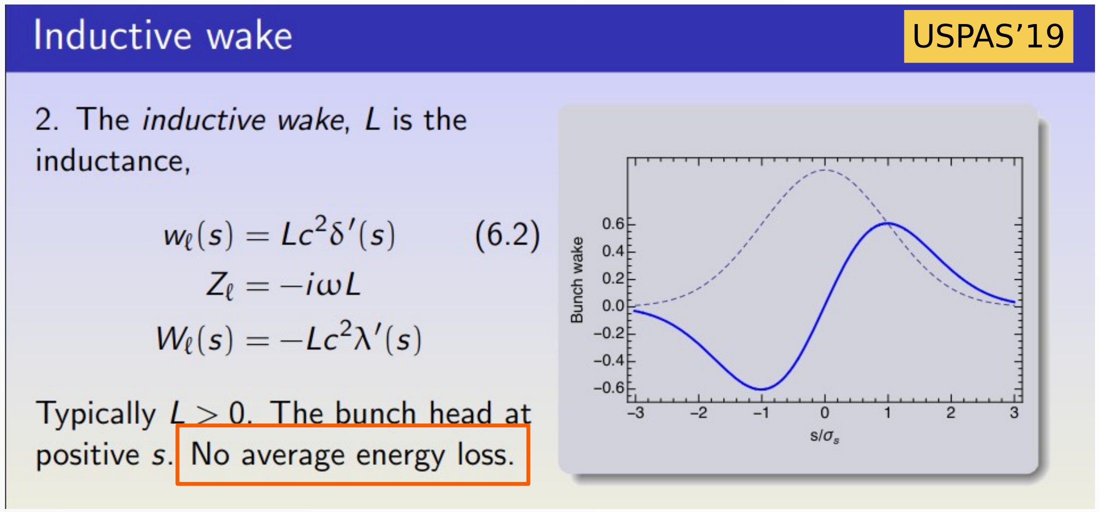
Angular dispersion-induced microbunching, W. Liu (SAPS)



Double harmonic scheme, X. Haisheng (HEPS)

Future Light Sources Workshop, Luzern 2023: fls2023.vrws.de

Bunch compression with self-induced wakefields

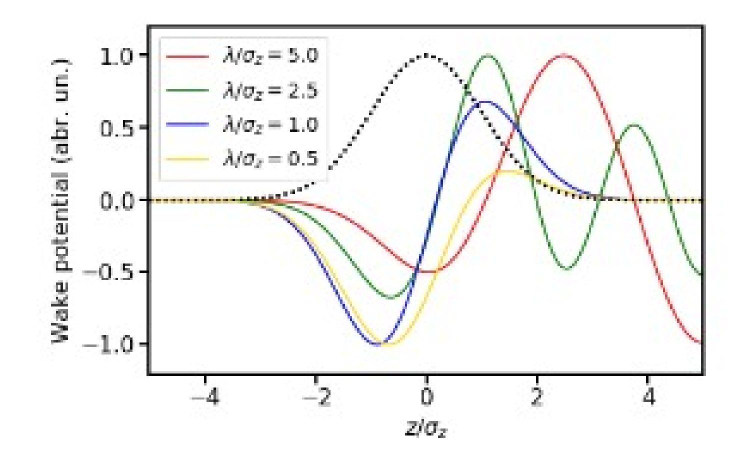


https://uspas.fnal.gov/materials/19Knoxville/lec%206.pdf

- Can compress the beam!
  - First noted by A. Gerasimov, FERMILAB-FN-62XX (1994)
  - Because compressing with RF is inefficient

$$\sigma_t = \frac{\sigma_E}{\omega_0}\sqrt{\frac{2\pi E\alpha}{heV_{rf}|\cos\phi_s|}}$$

- Can be a single-mode structure, dielectric or corrugated
  - Need **σ ~ λ**



Journal of Instrumentation

PAPER • OPEN ACCESS

Adiabatic bunch compression in storage rings from self wakes generated in Cherenkov waveguides

S.A. Antipov[1], I. Agapov[1], I. Zagorodnov[1] and F. Lemery[1]

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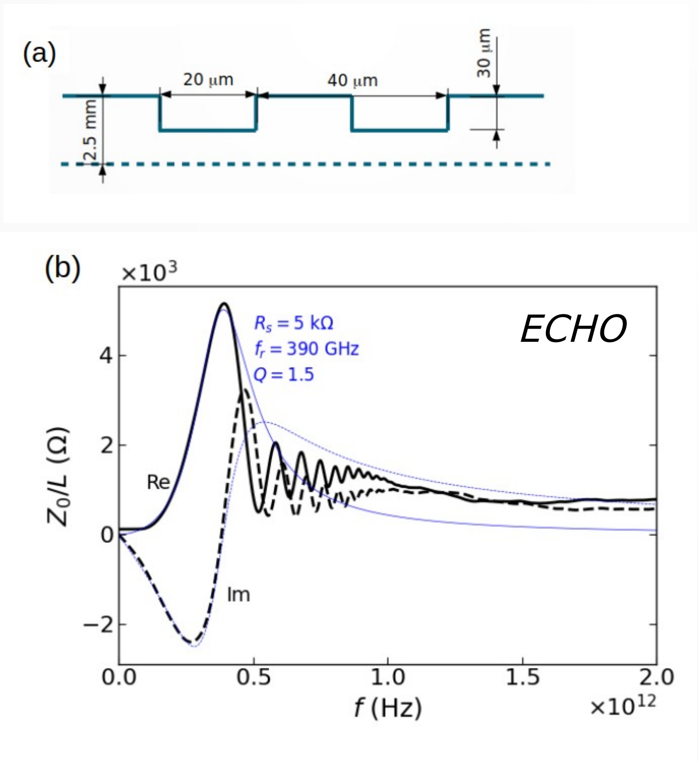
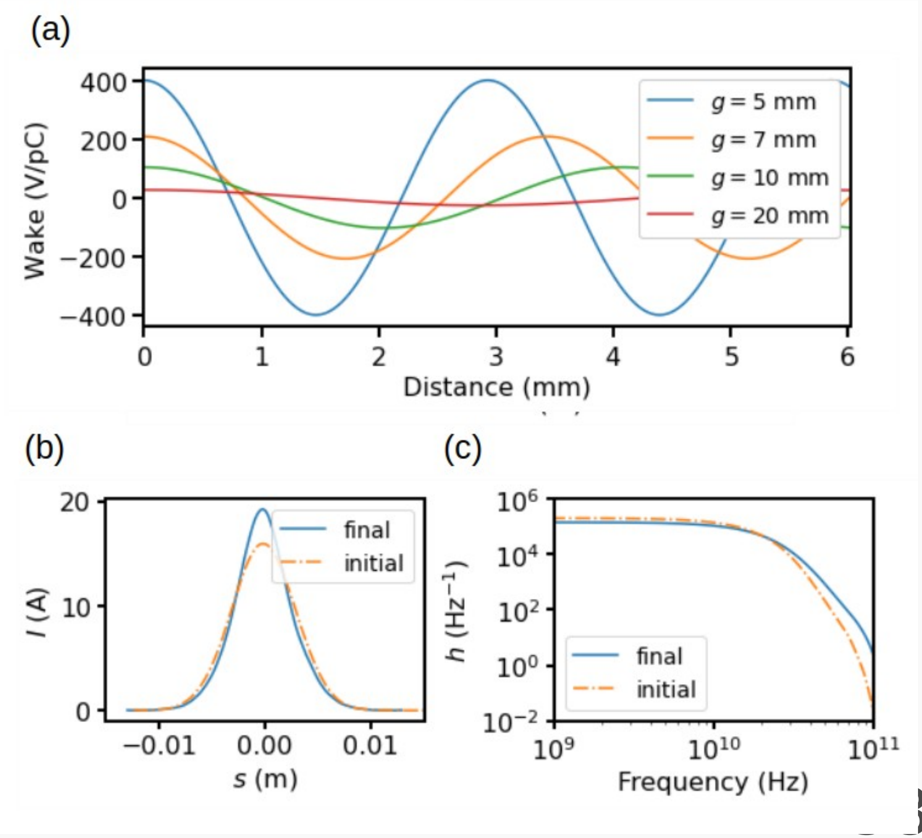
DOI 10.1088/1748-0221/18/07/P07024

Bunch compression with self-induced wakefields

- Example: 400 GHz structure for KARA low-α 1.3 GeV ring at KIT
  - Very short: only 30 cm
  - The gap adjusts the strength, not the frequency



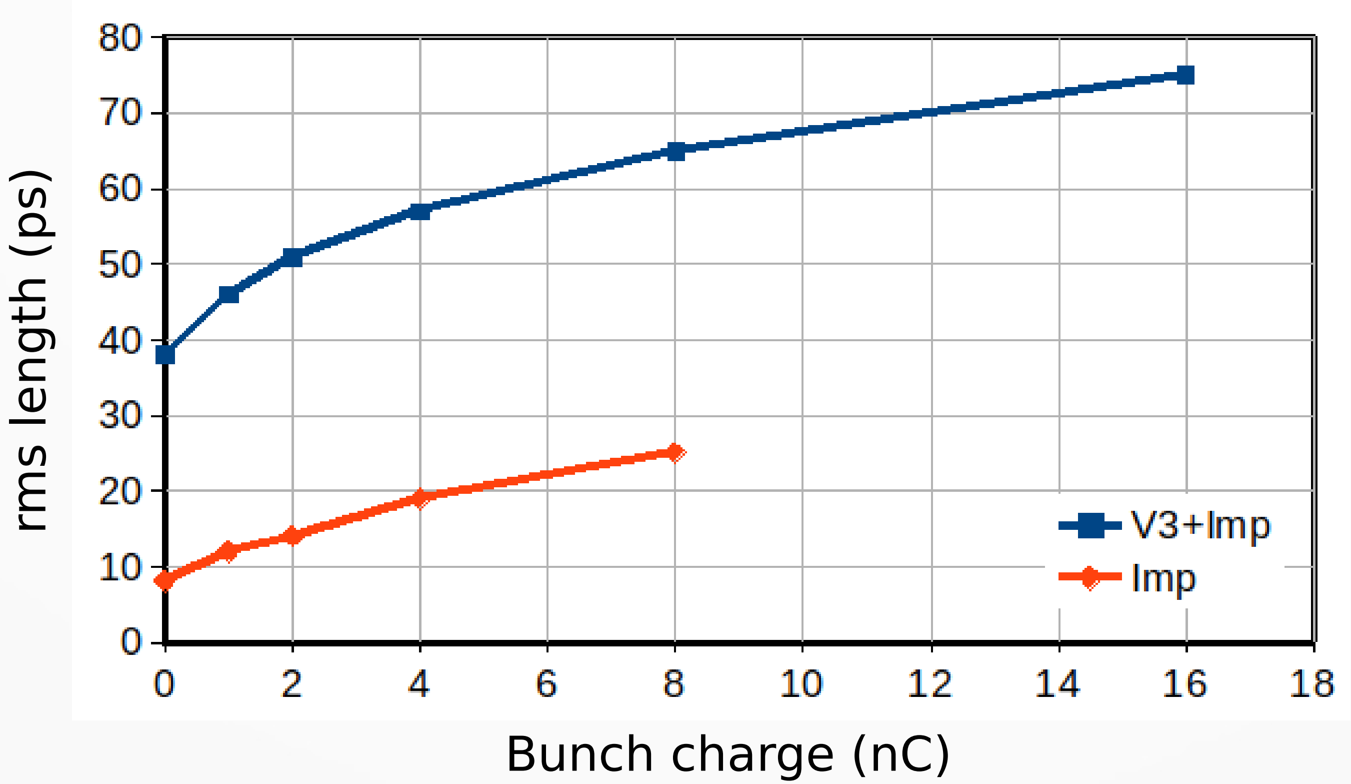
- Closing the gap – adiabatic bunch compression
  - +20% peak current
  - **x10** beam spectrum at **0.1 THz**



Thank you for your attention

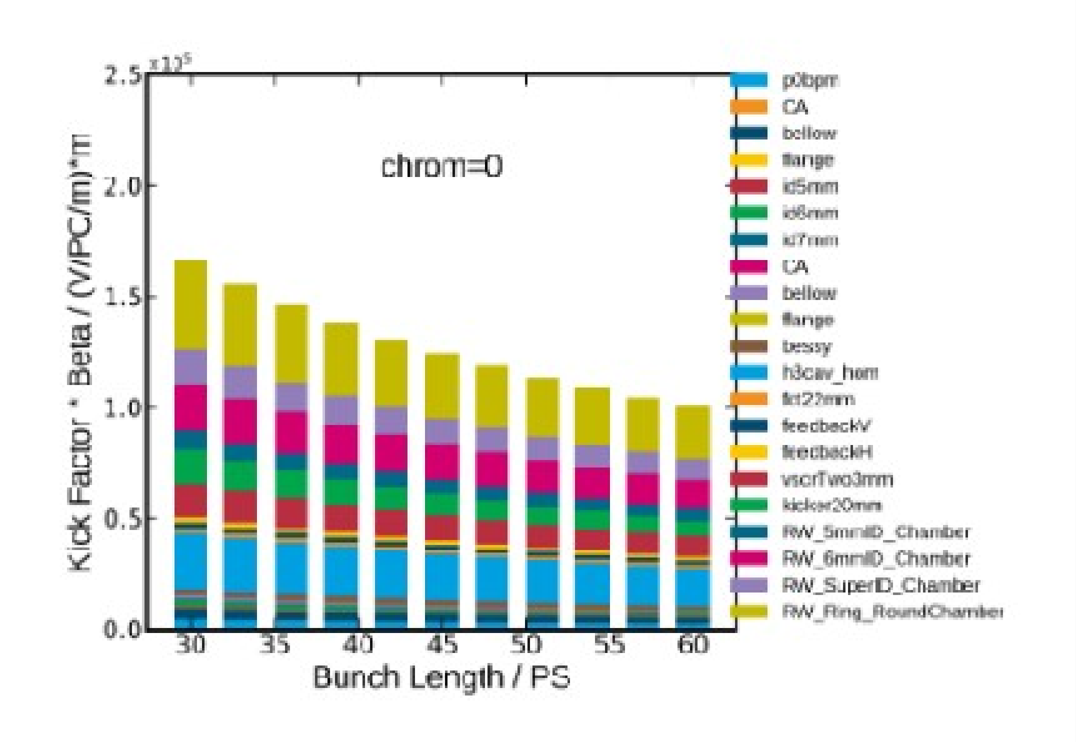
Bunch lengthening due to 3rd harmonic RF and impedance

- Tracking in ELEGANT
  - 10^5 macroparticles



Impedance

- Building the impedance model:
  - Including hardware as it is being designed
  - Geometric impedance simulated up to 100 GHz
- Resistive wall contribution dominates



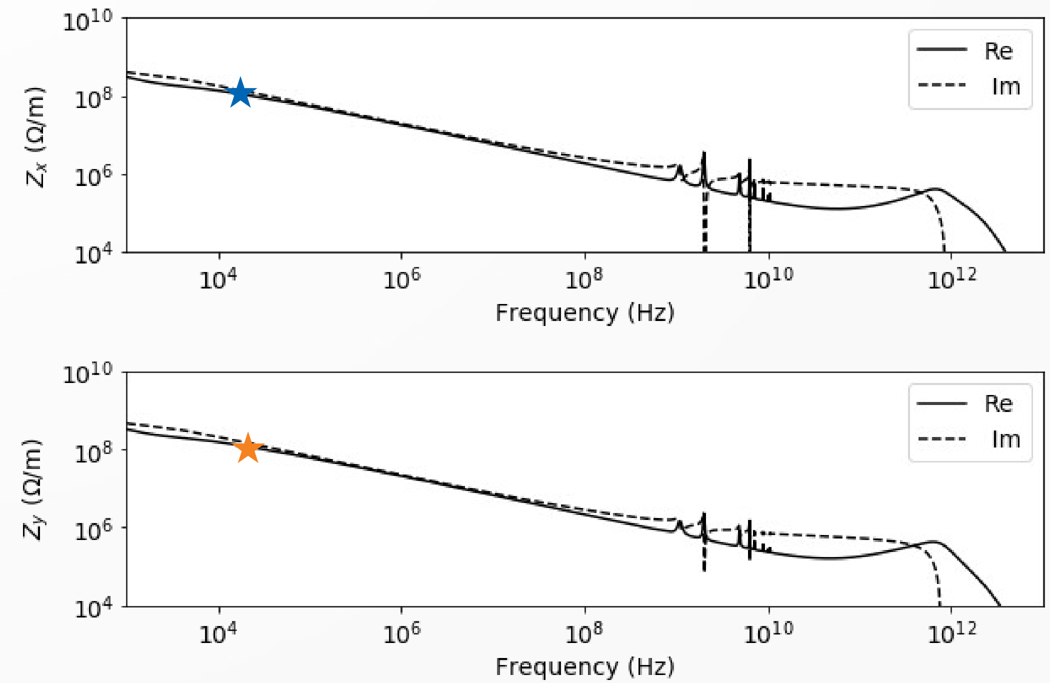
Simple analytical estimate: Air-bag model

Growth rate — Norm. beam cur. — Impedance — Chromaticity

Low intensity: $\Omega^l - \omega_\beta - l\omega_s \sim -i \frac{MN_b r_0 c}{2\gamma T_0^2 \omega_\beta} \sum_p Z(\omega') J_l^2(\omega'\tau - \chi)$ $\quad \omega' = (pM + \mu)\omega_0 + \Omega$

- At chromaticity 0: $\Gamma = \frac{M N_b r_0 c}{2\gamma T_0^2 \omega_\beta} \Re Z(\omega')$
  - Lowest betatron sidebands: (23.4, 35.1 kHz)
  - Growth times for full machine (M = 1920):

    (140, 80) revolutions
  - Note: this is an upper bound



Couple-bunch growth times for different operation modes: no feedback, no synchrotron damping

Growth rates in horizontal (vertical) planes

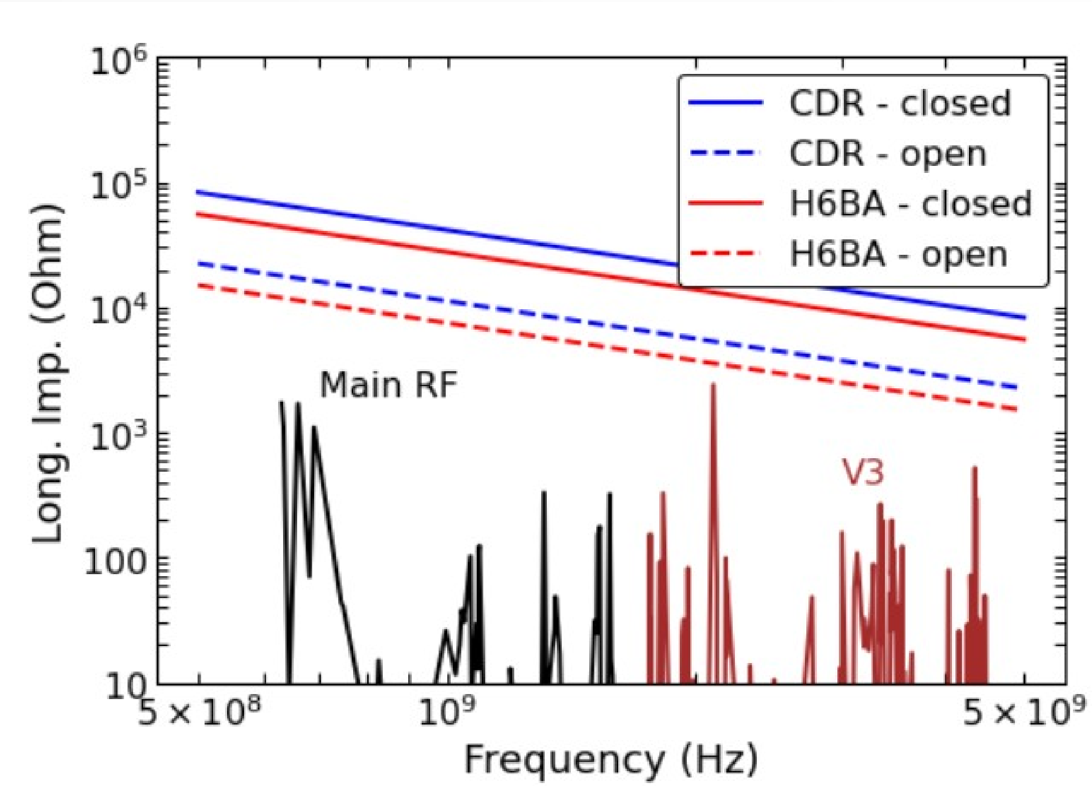
Filling scheme	Q' = 0	Q' = 5
Brightness 4 ns, 200 mA	250 (160) turns	3 530 (2080) turns
Brightness 2 ns, 200 mA	250 (160) turns	3 130 (2050) turns
Timing 80 b., 80 mA	770 (270) turns	17 150 (9370) turns
Timing 40 b., 80 mA	640 (110) turns	8 720 (5310) turns
Timing 80 b. 200 mA	160 (100) turns	5 510 (2360) turns

SR damping
~3 000 turns

Conservative limits: All HOMs have the same frequencies

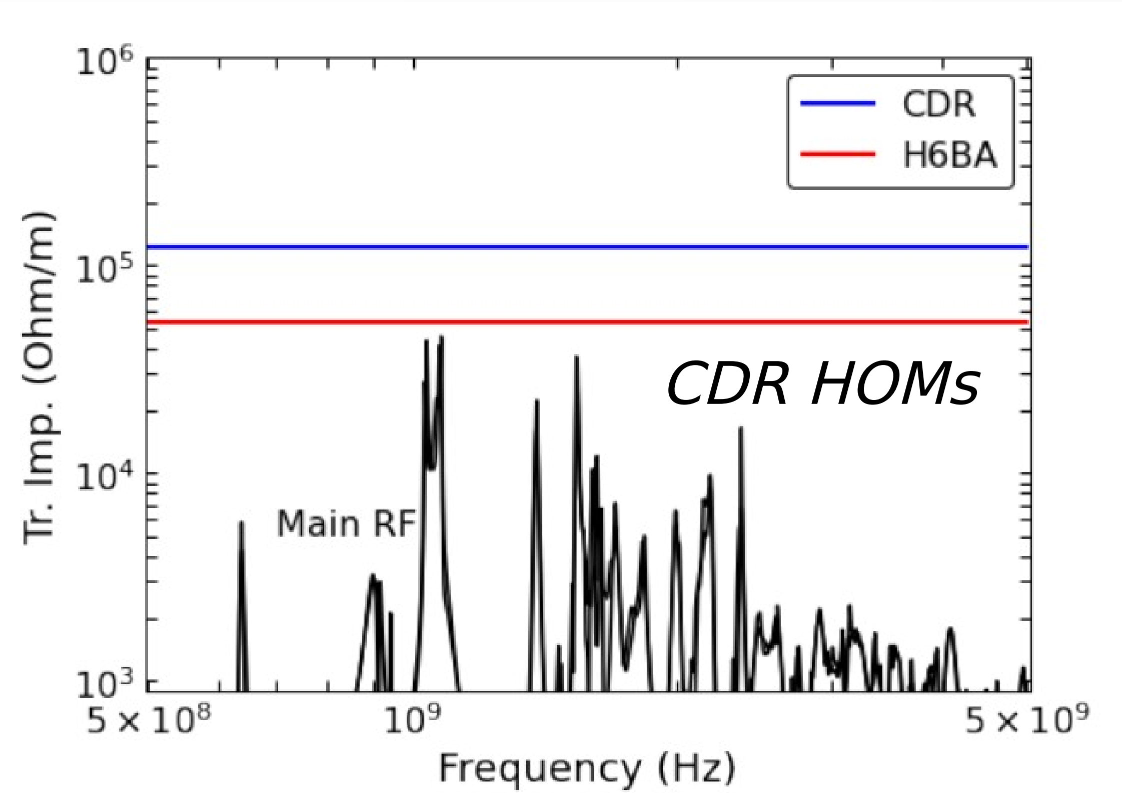
- Longitudinal stability

$$Z_{||}^{thresh}(f) = \frac{1}{f}\frac{1}{N_C}\frac{2EQ_s}{I_B \alpha_C \tau_s}$$



- Transverse stability

$$Z_{x,y}^{thresh}(f) = \frac{1}{f_{rev}}\frac{1}{N_C}\frac{2E}{\beta_{x,y} I_B \tau_{x,y}}$$



NHT Vlasov solver

- Physics:
  - Impedance: Single-bunch + couple-bunch modes
  - Chromaticity
  - Transverse feedback system (assumed ideal)

RF well Imp Damp CB

$$\frac{\Delta\omega}{\omega_s} X = \boxed{SX} - \boxed{iZX} - \boxed{igFX} + \boxed{CX},$$

- Discretizing the longitudinal distribution on a set of air-bags