Impedance And Collective Effects Studies For PETRA-IV

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On behalf of the PETRA-IV team

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

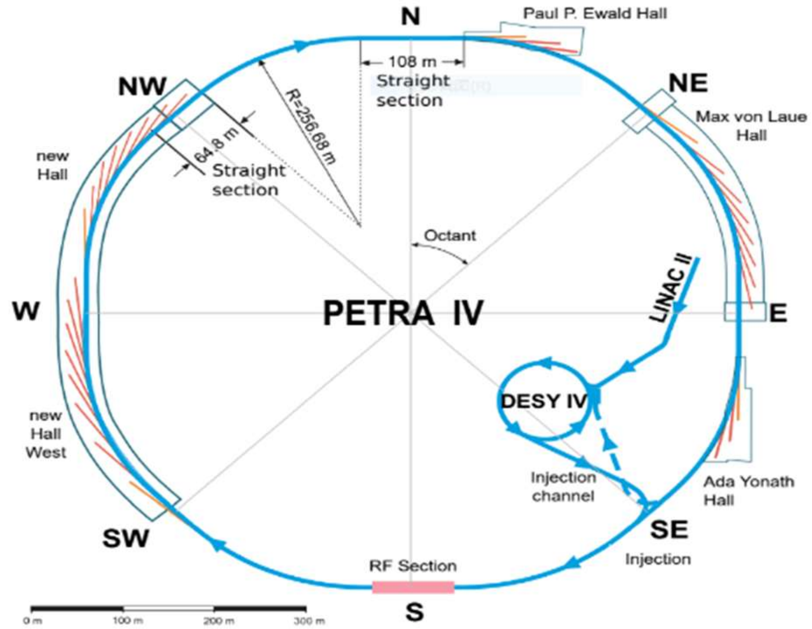
DESY.

Overview

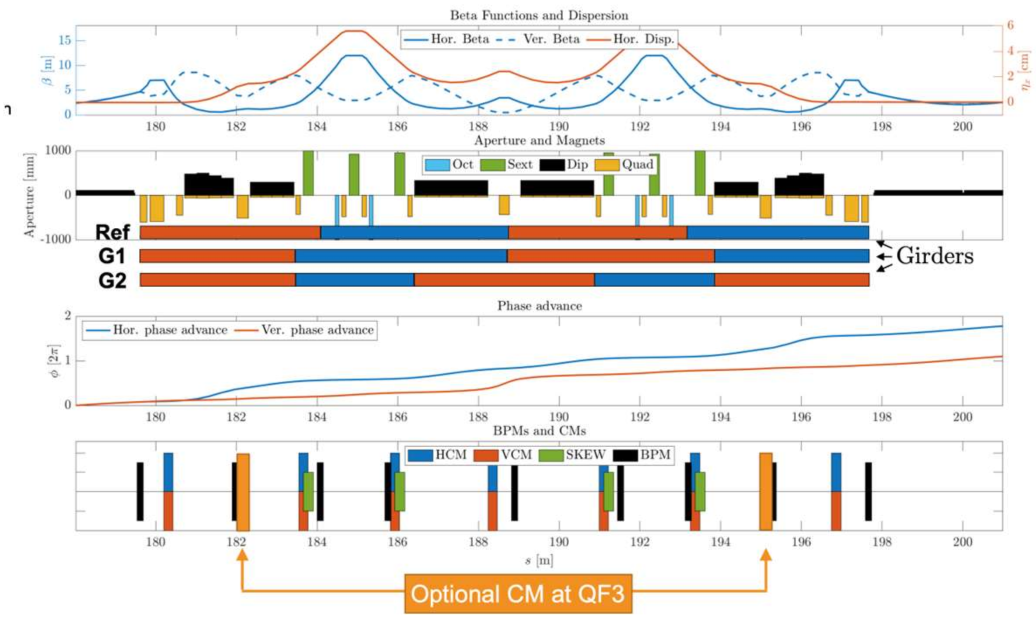
- Brief introduction on Petra4
- Impedance data base and impedance budget
- Single bunch effect
  - Microwave instability
  - TMCI
  - IBS and Touschek life-time
  - Single bunch current threshold as function of chromaticity
- Coupled bunch instability
  - Transverse coupled bunch growth rate from Nested Head-Tail Valosv solver
  - HOMS
  - Beam ion effect
  - Transient beam loading effect
- Summary and conclusion.

Lattice Overview

- Petra IV is upgrade of Petra III. Tunnel and existing experimental halls (Peter P. Ewald, Max von Laue, and Ada Yonath), and part of the infrastructure will be reused. An additional experimental hall will be constructed.
- H6BA lattice, 6GeV, 20pm natural emittance with damping wigglers



Layout of PETRA IV facility



Layout of the H6BA cell

Circumference	2304 m
nat. hor. emittance	20 pm
Coupling	0.2
energy spread	9.277e-4
mom. comp. factor	3.328e-5
nat. bunch length	2.3 mm
tune	135.18, 86.27
energy loss (ID closed)	4.30 MeV
chromaticity	5, 5
RF voltage (MC)	8 MV
harmonic number	3840
Max. total current	200 mA

Main parameters with damping wigglers

Operation modes

- Two different operation mode are considered (h=3840)
  - Brightness mode (1600 bunches, 200mA):
    - Periodical 80 trains in total, and each bunch train is 48 rf buckets long.
    - In each train, there are 20 bunches occupying every other bucket, following 8 empty buckets: 48 = (20*2 + 8)
  - Timing mode (80 bunches, 80mA):
    - 80 bunches uniform filling, (1mA/bunch)

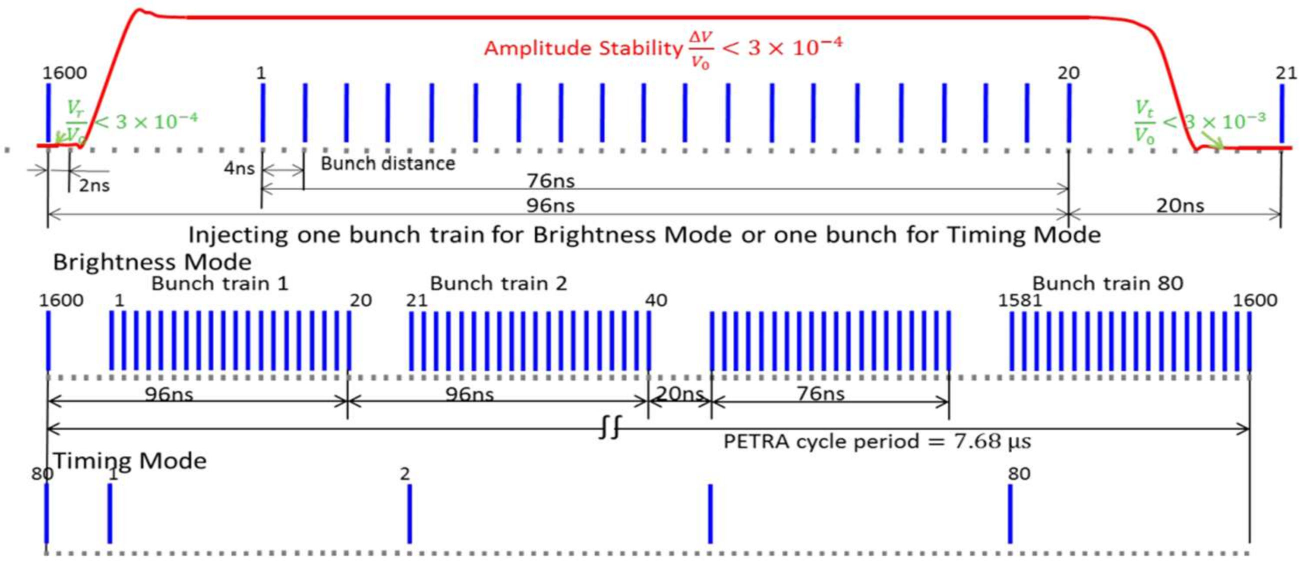


Figure 6.29.: *Injection fill pattern scheme for PETRA IV on-axis injection.*

Brightness mode filling scheme

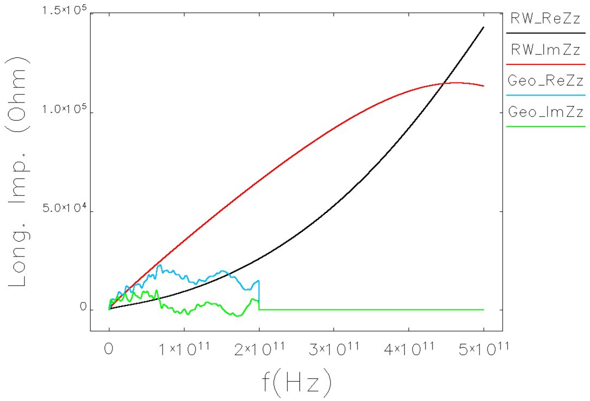
Impedance table

- GEO impedance.
  - Wake potential of each element is from GDFIDL (1mm leading bunch)
- RW impedance (ImpedanceWake2D simulation).
  - From ID Chambers
  - From the rest of the ring

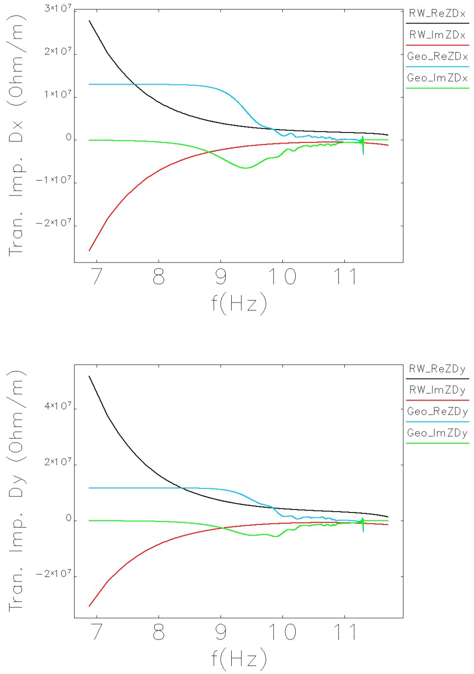
Courtesy of Yong-Chul Chae and Sergey Antipov

	Element	Number	BetaX/BetaMin/BetaMax	BetaY/BetaMin/BetaMax	Beta Z	Comment
	General components					
p0bpm.stdwake	BPM	788	6.18	7.31	1	Exact BPM locations
CA.stdwake	Absorber	576	3.8	4.73	1	Radiation absorbers at arc BPMs. Exact locations
bellow.stdwake	Bellow	375	2.71	4.25	1	CDR Estimate number, updated betas
flange.stdwake	Flange	375	2.71	4.25	1	CDR Estimate number, updated betas
	ID Arcs (19 x 5 m + 5 x 10 m)					
id6mm.stdwake	ID 6 mm	17	5.04	5.04	1	Average betas over the ID
id5mm.stdwake	ID 5 mm	4	5.04	5.04	1	Exact number of ID with smaller gaps is an estimate. Average betas over the ID
id7mm.stdwake	ID_10 7 mm	5	10.25	10.25	1	Super ID. Average betas over ID
p0bpm.stdwake	ID BPM	0	0	0	0	No small aperture ID BPMs foreseen
CA.stdwake	Absorber	96	5.85	4.4	1	Preliminary locations, sketch from Katharina
bellow.stdwake	Bellow	96	5.7	4.3	1	Preliminary locations, sketch from Katharina
flange.stdwake	Flange	96	5.8	4.4	1	Estimate
	Long straight section					
bessy.stdwake	RF	24	20	20	1	Estimate. RF section was re-optimized to lower average betas
h3cav_hom.stdwake	3V RF	24	20	20	1	Estimate. RF section was re-optimized to lower average betas
fbcav	Long FB	8	averBetax	averBetay	0	No Longitudinal feedback foreseen
fct22mm.stdwake	FCT	6	averBetax	averBetay	1	Fast current monitor
	Short straight section					
feedbackH.stdwake	Tr FB H	4	12.5	15	1	Rough estimate
feedbackV.stdwake	Tr FB V	4	12.5	15	1	Rough estimate
vsrTwo3mm.stdwake	Collimators	4	12.5	15		A few will be needed, exact number to be finalized. Assuming average betas
	Injection straight section					
kicker20mm.stdwake	Inj Kicker	30	10	10	1	Preliminary estimate for 2 ns spacing, top-up stripline kicker
kicker20mm.stdwake	Ext Kicker	0	0	0	0	No extraction foreseen
final Geo impedance is given to GeoImp.sdds						
	ID Chamber RW impedance					
SuperID_Chamber.sdds	SuperID	5	6.08/4/10.25	6.08/4/10.25		10m long for each
5mmID_Chamber.sdds	5mmID	4	3.14/2.2/5.04	3.14/2.2/5.04		5m long for each
6mmID_Chamber.sdds	6mmID	17	3.14/2.2/5.04	3.14/2.2/5.04		5m long for each
	Ring Round chamber RW impedance					
RW_Ring.sdds		1	averBetax	averBetay		2304

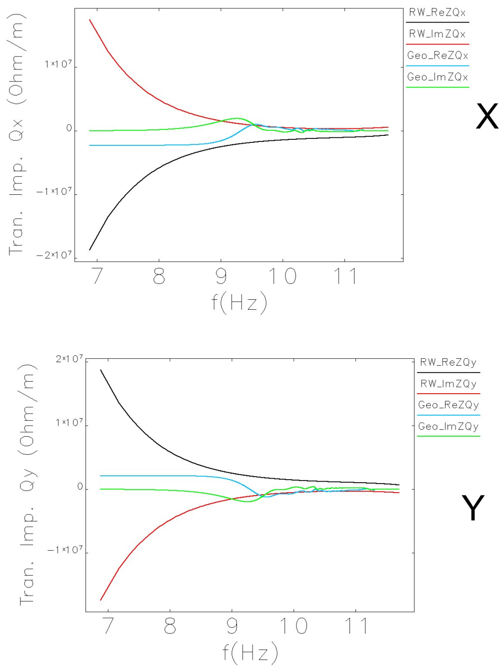
Total Impedance and wakefield.



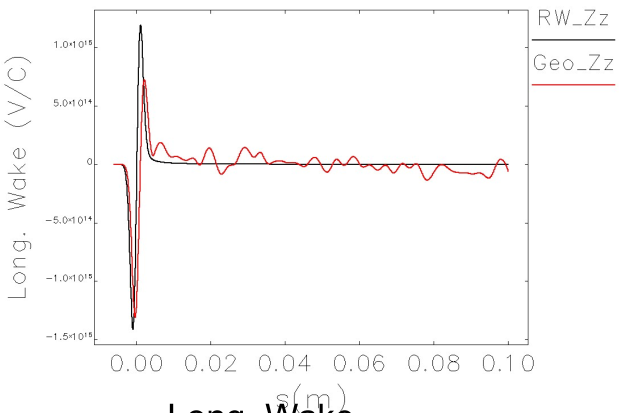
Long. Imp



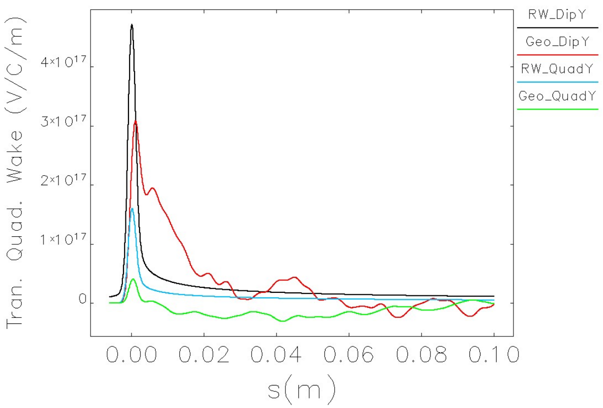
Trans. Dipole



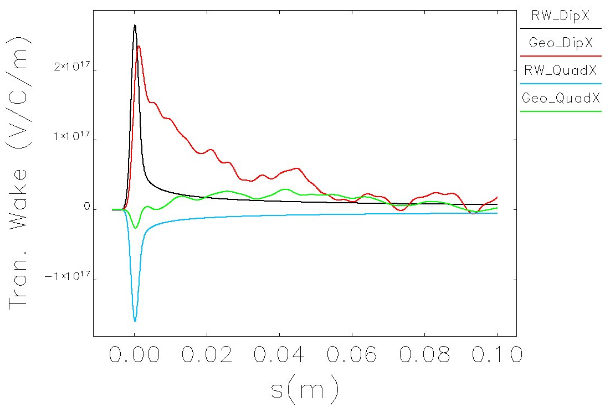
Trans. Quad



Long. Wake



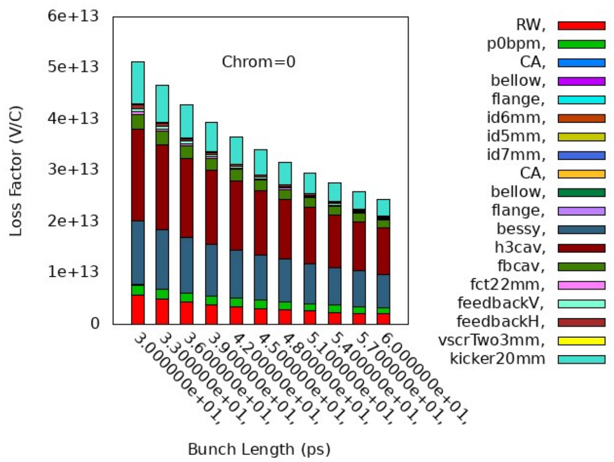
Trans. Wake (Y)



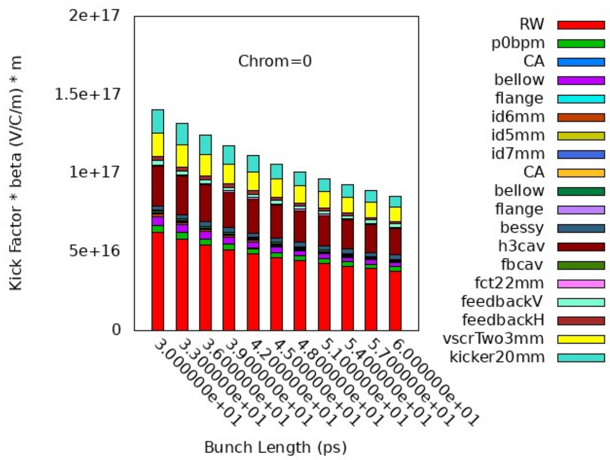
Trans. Wake (X)

Kick and loss factors (1mA)

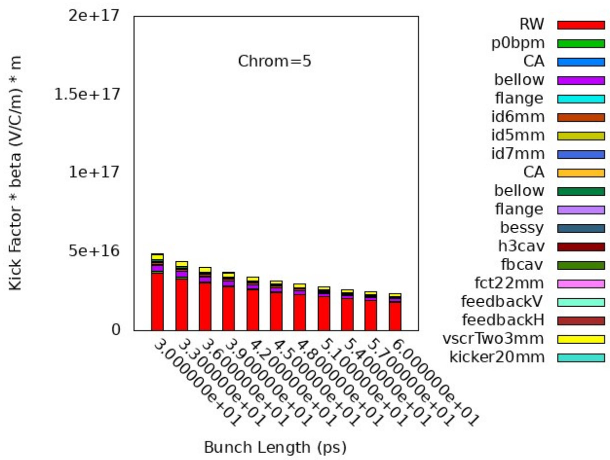
- Kick and loss factor as function of bunch length. Bunch length varies from 30 ps to 60 ps
- bunch length with 42 ps is nominal setting when a harmonic cavity is included
- Loss factor: RW, BPM, cavities, flanges
- Kicker factor: RW, BPM, bellow, id taper, cavities, vscrTwo3mm, kicker20mm.
- With zero chromaticity, RW supplies 50% of the kick factor; at chromaticity 5, RW supplies 80% of the total kicker factor
- At chromaticity 5, kicker factor is significantly reduced, roughly by a factor of 3.



loss factor Vs bunch length



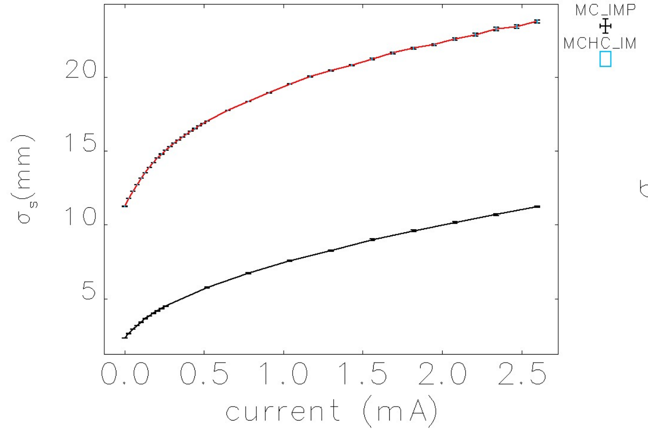
Kick factor Chrom=0



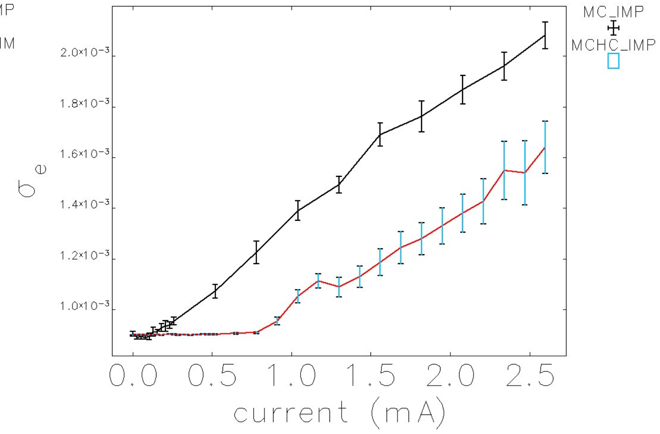
Kick factor Chrom=5

Single bunch effect

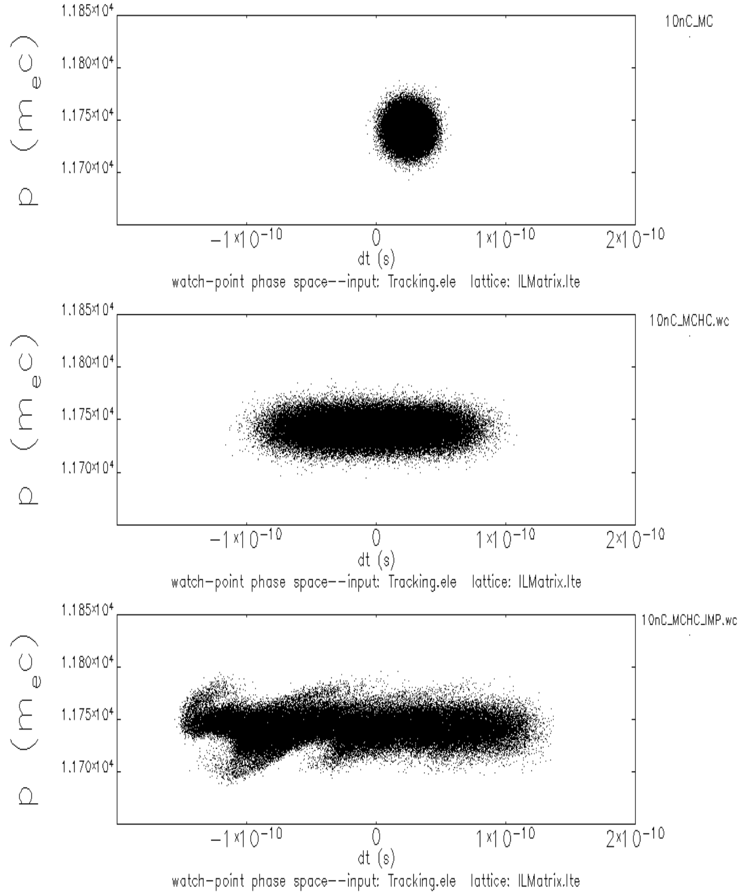
MWI (With and W/O harmonic Cavity)



Bunch length



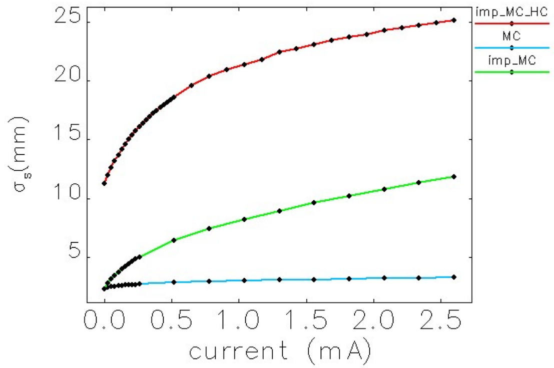
Energy spread

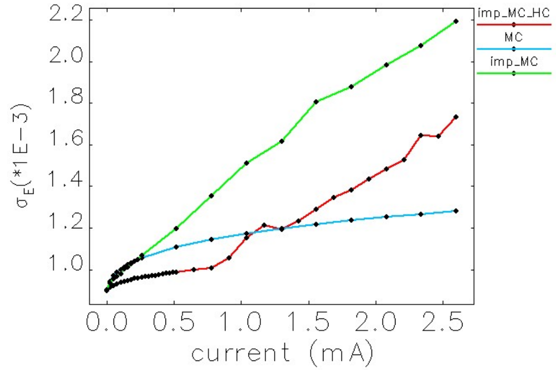


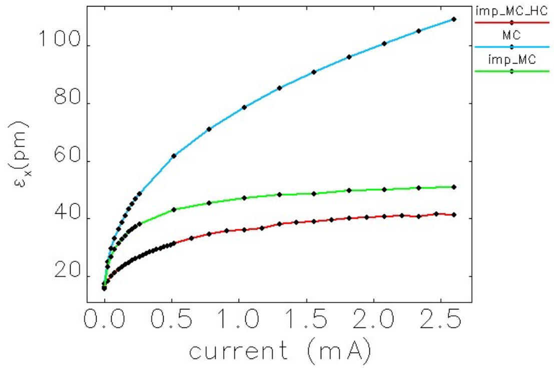
- **Bunch length Vs bunch current**
  - **Ideal cavity model.**
  - **At 0 mA, harmonic cavity increase the bunch length by a factor of 5.**
  - **At 2.5mA, harmonic cavity increase the bunch length by a factor of 3.**
- **Energy spread Vs bunch current**
  - **Longitudinal microwave instability increased to 0.8mA by the harmonic cavity**
- **Longitudinal phase space MC/MC_HC/ MC_HC_IMP at 10nC (1.3mA).**

IBS and touschek lifetime (coupling 0.2)

- We investigate the IBS effect
  - Pure IBS (MC only)
  - MC + Impedance
  - MC + Impedance + HC
- Pure IBS
  - Very weak bunch lengthening effect
  - 30% energy spread increasement till 2.5 mA
  - Significant transverse emittance growth
- longitudinal impedance and HC lead to
  - Longer bunch length
  - Significantly reduce the transverse emittance growth, (by a factor of 3 at 2.5 mA)



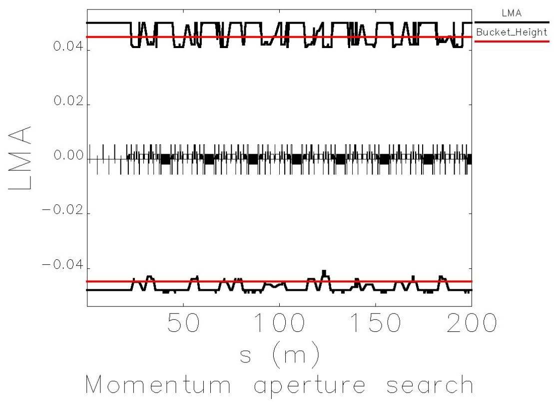




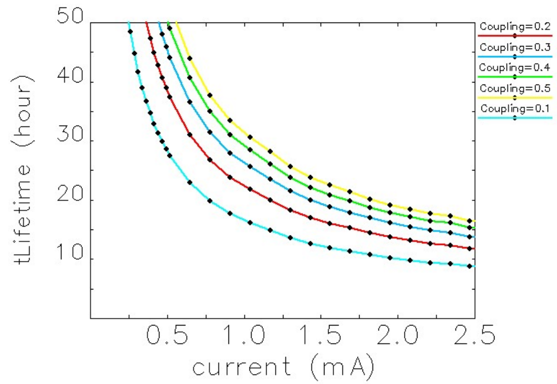
IBS and touschek lifetime (coupling 0.2)

- **TouschekLiftetime in Elegant package code is used**
- **Local momentum is about 4.4% on average (no errors) for nominal 8MV main cavity voltage, 20% coupling.**
- **1mA/2mA (20h, 15h)**

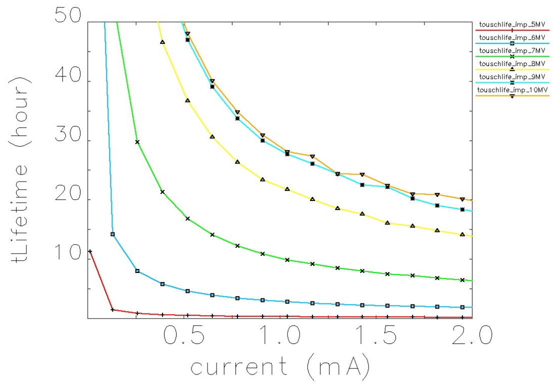
LMA/8MV



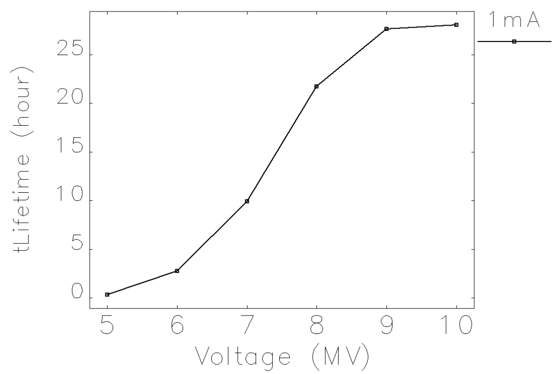
Lifetime (coupling)



- **Toucheklife time as function of beam current and main cavity voltage.**
- **MC voltage varies from 5MV to 10MV, meanwhile HC ensure the ideal bunch lengthening condition.**
- **Higher main cavity voltage (as 9 MV) will bring us a better life-time. But - no more benefit if goes further beyond 10 MV**



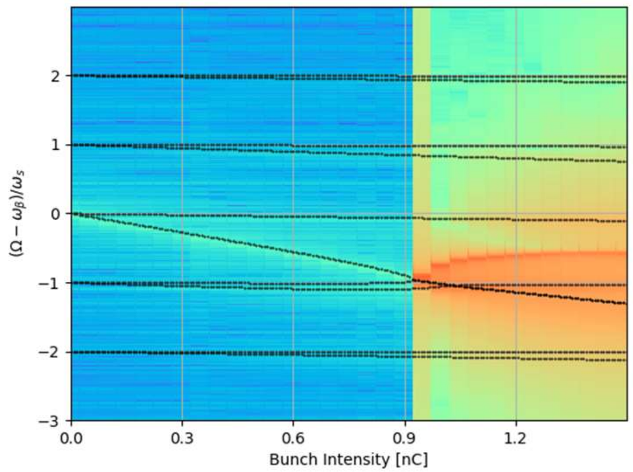
Lifetime (MC Voltage)



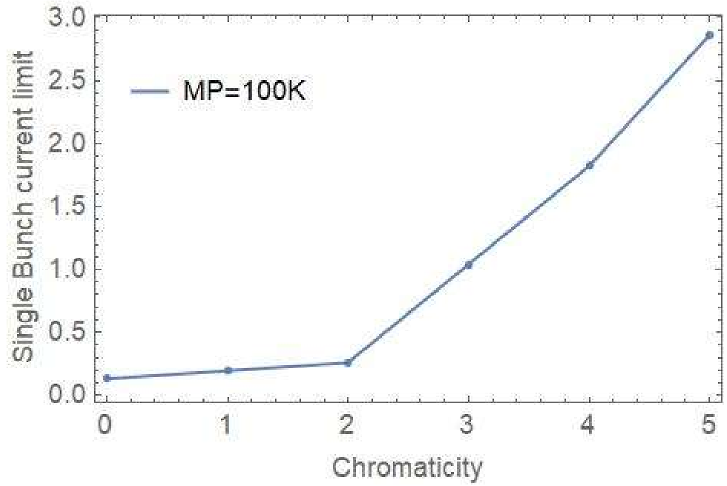
Lifetime (1mA)

TMCI and beam current threshold as function of chromaticity

- TMCI simulation, 0.12mA (0.9nC) threshold, frequency shifts from Vlasov solver (CETA) agree well with tracking below the threshold. For a better comparison, only the main cavity is included.
- To decide the single bunch threshold with the total impedance at hand, the longitudinal, transverse dipole and quadrupole impedance, ideal 3rd harmonic cavity are applied in simulation.
- Dynamical aperture is set as particle loss criteria (\pm 6mm, \pm 15mm)
- Single bunch current threshold is decided by the lowest current with non 100% transmission.
- Chromaticity 5 roughly ensures 2.9mA (22nC) single bunch current.



Frequency shift / bunch intensity



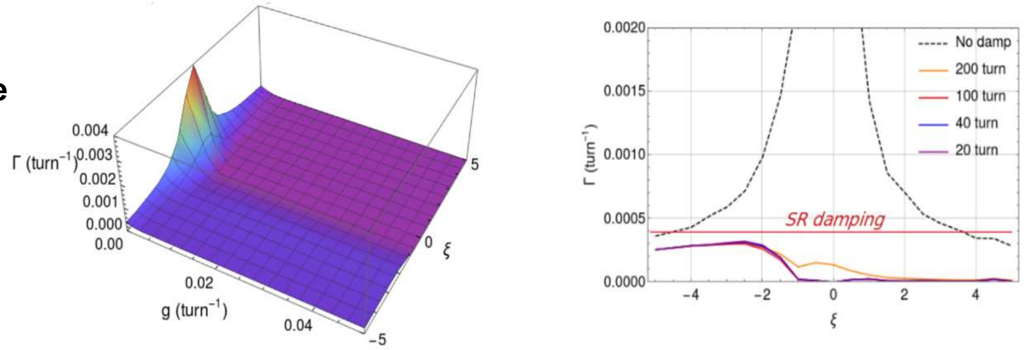
Single bunch threshold / chromaticity

Coupled bunch effect

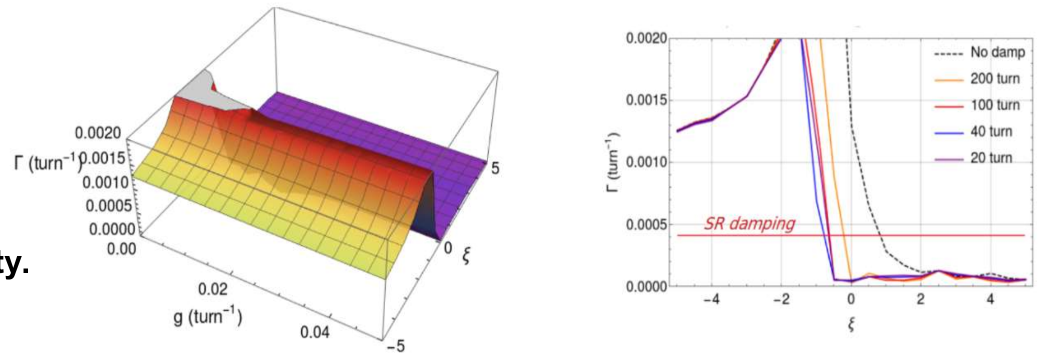
Nested Head-Tail Vlasov solver (transverse)

- **Impedance data at current version.**
- **Evaluate the transverse coupled bunch mode growth rate as function of chromaticity and feedback gain**
- **Growth rate would reach large value at zero chromaticity without feedbacks.**
- **Chromaticity 5 decrease the growth rate significantly.**
- **Further a 100 turns or stronger feedback stabilize the transverse motion for both brightness mode and time mode.**
- **We do not expecting transverse coupled bunch instability.**

Brightness mode, 4 ns



Timing mode, 80 bunches



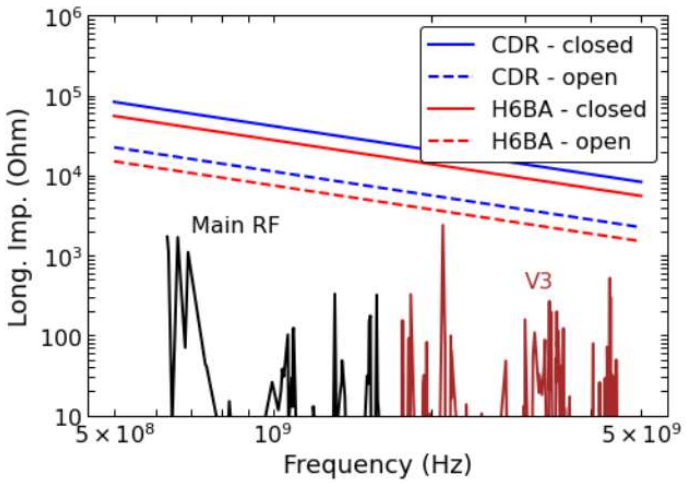
Courtesy of Sergey Antipov

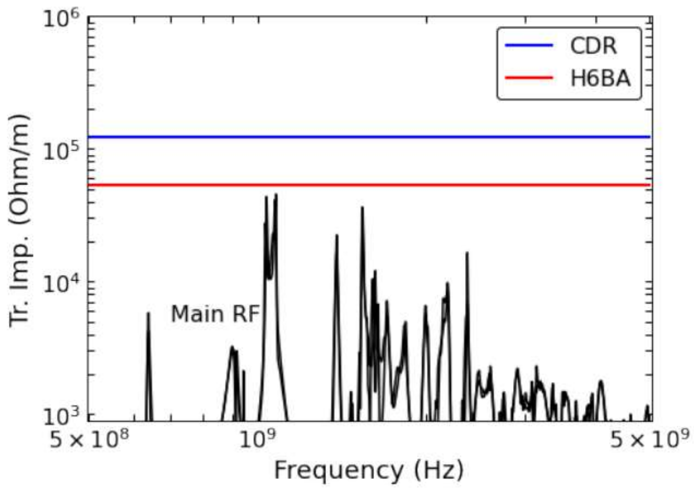
High order modes (HOMs)

- If HOMS are excited, would be hard to suppress due to high frequency of the driving modes.
- To counter HOMs, a broadband HOM damping scheme will be used in the cavities.
- Threshold impedance by equating the radiation damping time with the multi-bunch instability growth time.
- With a HOM coupler, HOMs are well damped below the threshold impedance.

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

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





Courtesy of Sergey Antipov

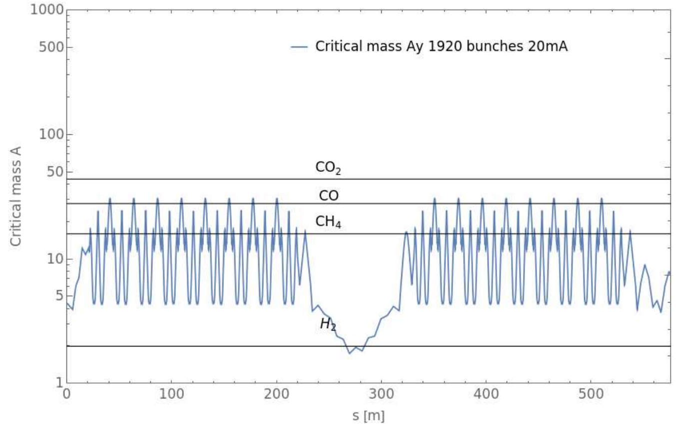
Beam-Ion effect

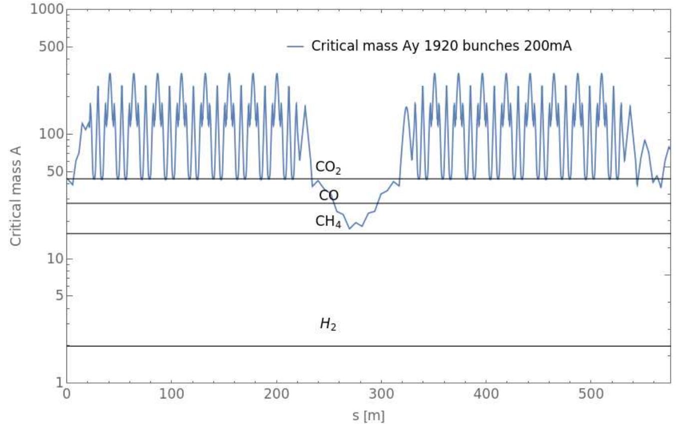
$$A > A_{\text{th}} = \frac{N_b r_p \Delta T_b c}{2\sigma_{x,y}(\sigma_x + \sigma_y)},$$

- **Smaller beam current itself also indicates a weaker interaction between electron and ion.**
- **However, smaller beam current indicates more ion species can be trapped, which conversely increases the interaction between ion and electron.**
- **Higher beam current generated more ions at each interaction**
- **However, higher beam current over-focus ions, which easily got lost**
- **Ion effect is more significant at medium current range.**

- **In the simulations bellow, we mainly shows results with the APS ions species.**

Ion trapping along the ring

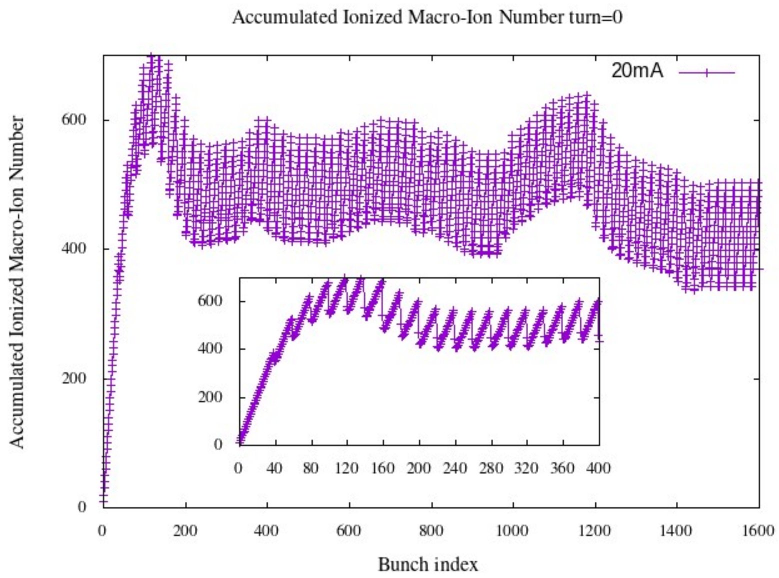


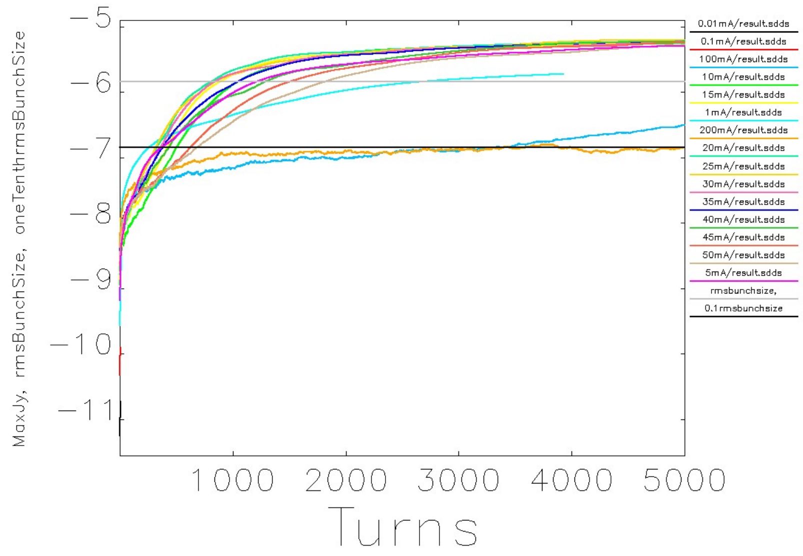


Gas compositions in different machines.						
H_2	CH_4	H_2O	CO	CO_2	Ring	condition
	0.16	0.1	0.28	0.44	SPEAR3	
0.96	0.01		0.01	0.02	MAX IV	
	0.9				PETRA 4	simulation with active NEG
	0.02		0.36	0.4	PETRA 4	simulation with non-active NEG
0.43	0.08		0.36	0.13	APS-U	APS-U 50% NEG coating, with 1000 Ah beam scrubbing
0.35	2.1		2	2.92		Cross section Mb [2.E-22/m^2]

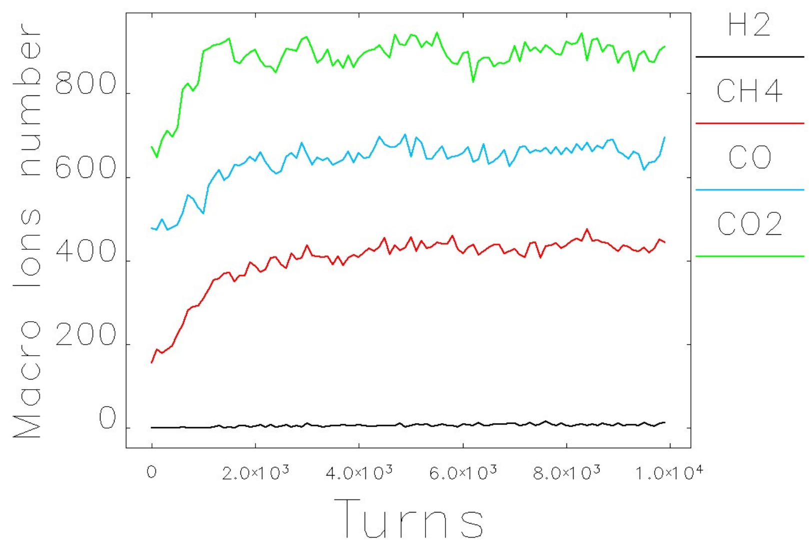
Beam-ion effect @ brightness mode

- In-house developed code CETASIM is used in simulation.
- 1nTorr total ion gas pressure, 300K
- How ions are accumulated in simulation in the first turn
- Max action Jy among 1600 bunches at each turn is stored to get the beam-ion growth rate further, (data within the range of (0.1,1) rms beam size)
- At 20mA, H2 ions are hardly trapped as expected by ion trapping condition.





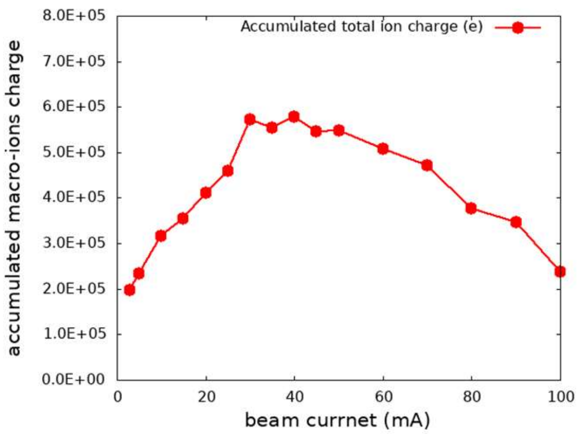
MaxJy VS tracking turns



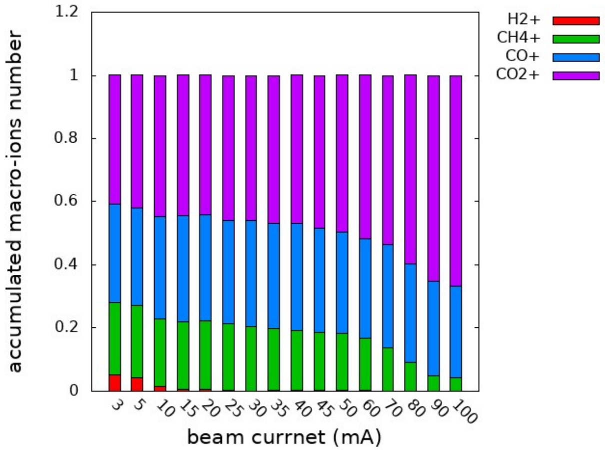
macro-ions numbers VS tracking turns (20mA)

Beam-ion effect @ brightness mode

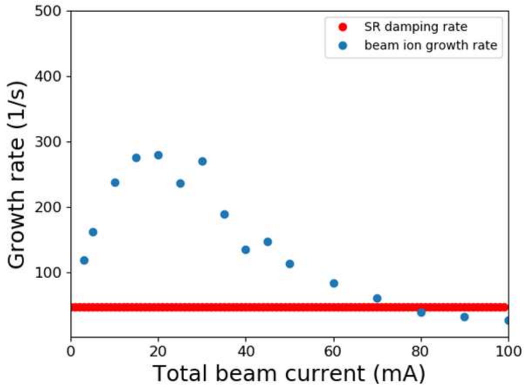
- In low beam current region, less ions are generated per interaction.
- In high beam current region, more ions are generated per interaction, but more ions are over-focused and get lost also
- With current increased, less and less lighter ions can be trapped .
- Beam ion instability takes place within 70mA.
- Growth rate at 20 mA 300 (1/s) is around 450 turns.
- Current bunch-by-bunch feedback is supposed to supply 20 turns damping rate at maximum.
- Beam-ion effect is very weak in timing mode.
- Beam-ion effect is very weak with Max-IV gas species.



Total ion charge after 10K turns



Ion species ratios after 10K turns



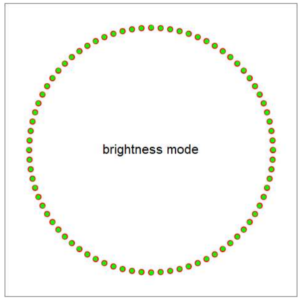
Instability growth rate

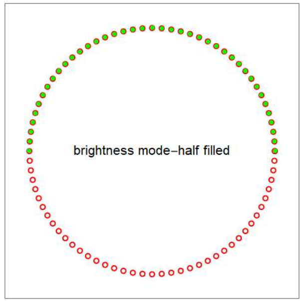
	H_2	CH_4	H_2O	CO	CO_2	Ring
Initial	0.43	0.08		0.36	0.13	APS-U

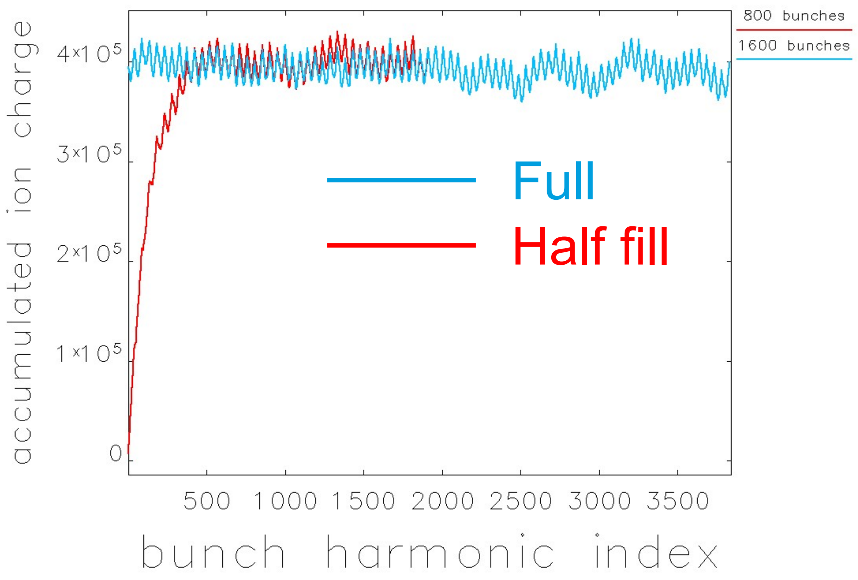
Beam-ion effect @ brightness mode

- Nominal brightness filling patter: 3840 = 80 * (20*2 +8)
- Half-fill filling pattern: 3840 = 40 * (40 +8) + 1600

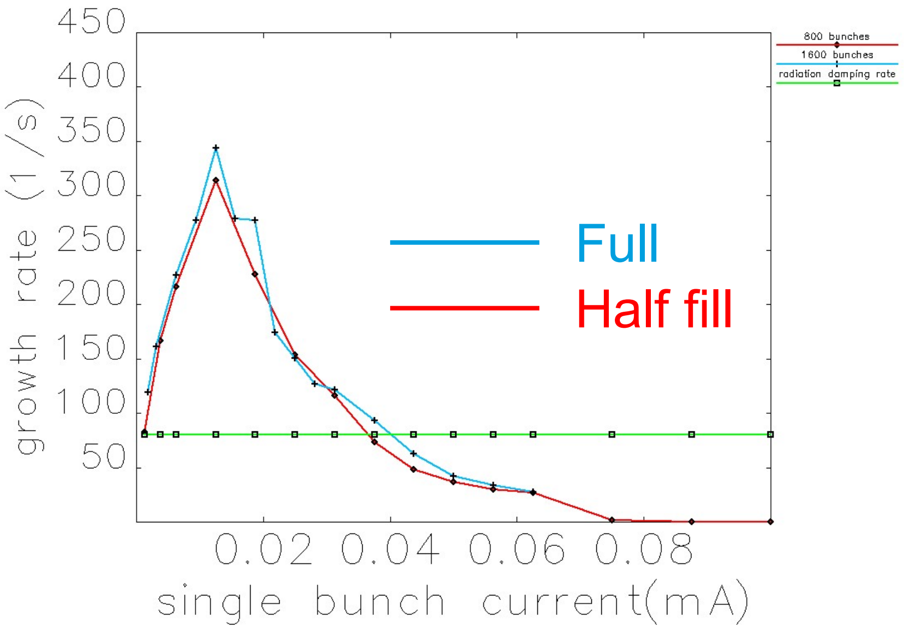
- We verified that the long gap can clean ions.
- Maximum number of accumulated ion is comparable.
- As a result, the bam ion growth rate are almost the same ("fast-ion" mechanism within one turn)
- Long gap does not help too much to mitigate the ion effects in our case.







macro-ions charge in the second last turn @20mA



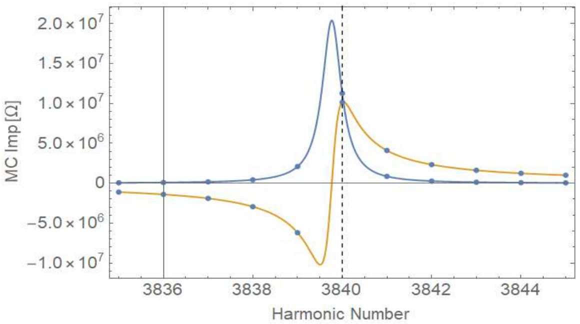
Beam-ion instability growth rate Vs beam current

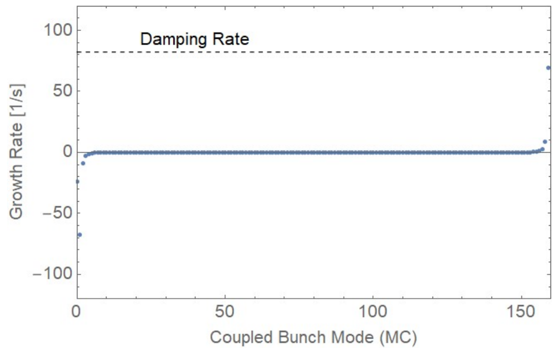
Transient beam loading @ brightness mode

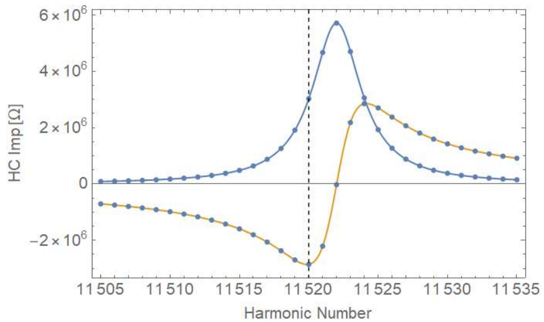
- A strong transient beam loading due to non-uniform filling scheme and coupled bunch instability is foreseen due to the cavity fundamental mode.
- Double active RF system.
- However, if the low lever RF control loop can be applied appropriately, the impedance of the fundamental mode beam can sample will be significantly reduced.

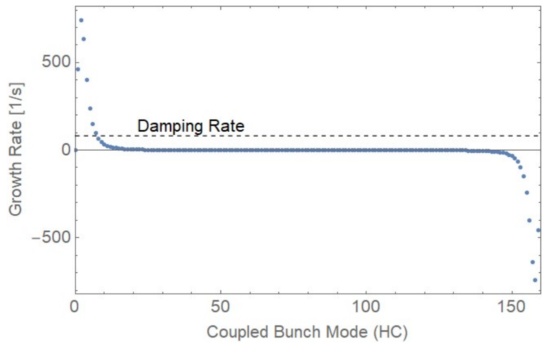
- In blow, we show how bunch length is affected by the transient beam loading effect in spite of the coupled bunch instability.

	Main cavity	3rd Harmonic Cavity
Quality factor Q_0	29600	17000
Loaded Quality factor Q_L	7400	2700
Cavity coupling factor β	3	5.3
Shunt impedance (Ohm)	8.16E+6	36E+6
200 mA		
Opt. Tune Psi	-0.747	0.697
Cavity Vol. (V)	8E+6	2.391E+6
Cavity Phase(rad)	1.08	-1.746
Beam Induced Vol. (V)	5.983E+6	1.7418E+6
Beam Induced Phase (rad)	2.393	-2.442
Generator Vol. (V)	8.67e+8	1.535E+6
Generator Phase	0.3523	-0.928







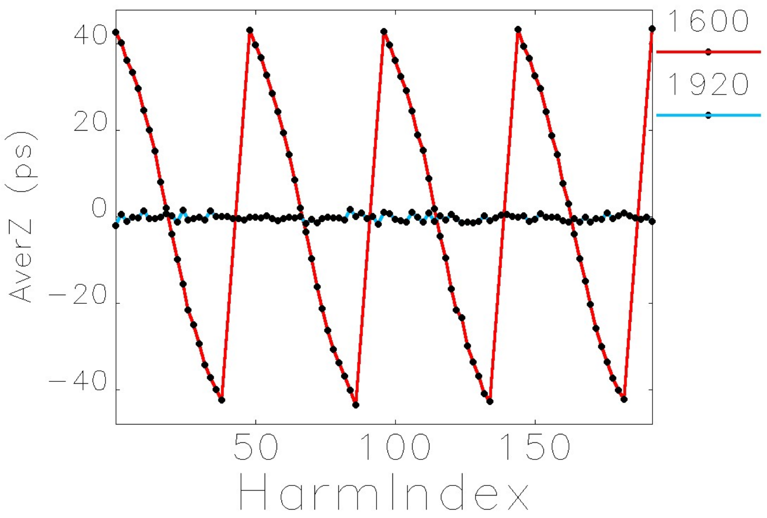


Growth rate 200mA

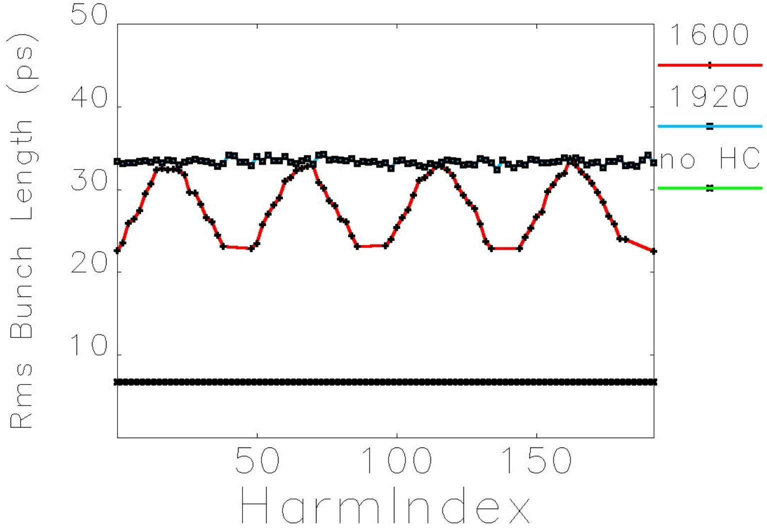
Transient beam loading @ brightness mode (lattice version pg23)

- 5K macro-particle per bunch@CETASIM
- The coupled bunch instability is not excited in simulation.
- Case 1 (uniform 1920 bunches)
  - In each bunch train: 48 = 24*2
  - No transient effect is expected, bunch center stays around 0.
  - Rms bunch length (8 ps->32ps) for all bunches
- Case 2 (non-uniform brightness mode)
  - In each bunch train: 48 = (20*2 + 8)
  - Bunch center and bunch length show periodic “pattern”
  - Average bunch Length: 8.51 mm

Bunch Center Shift



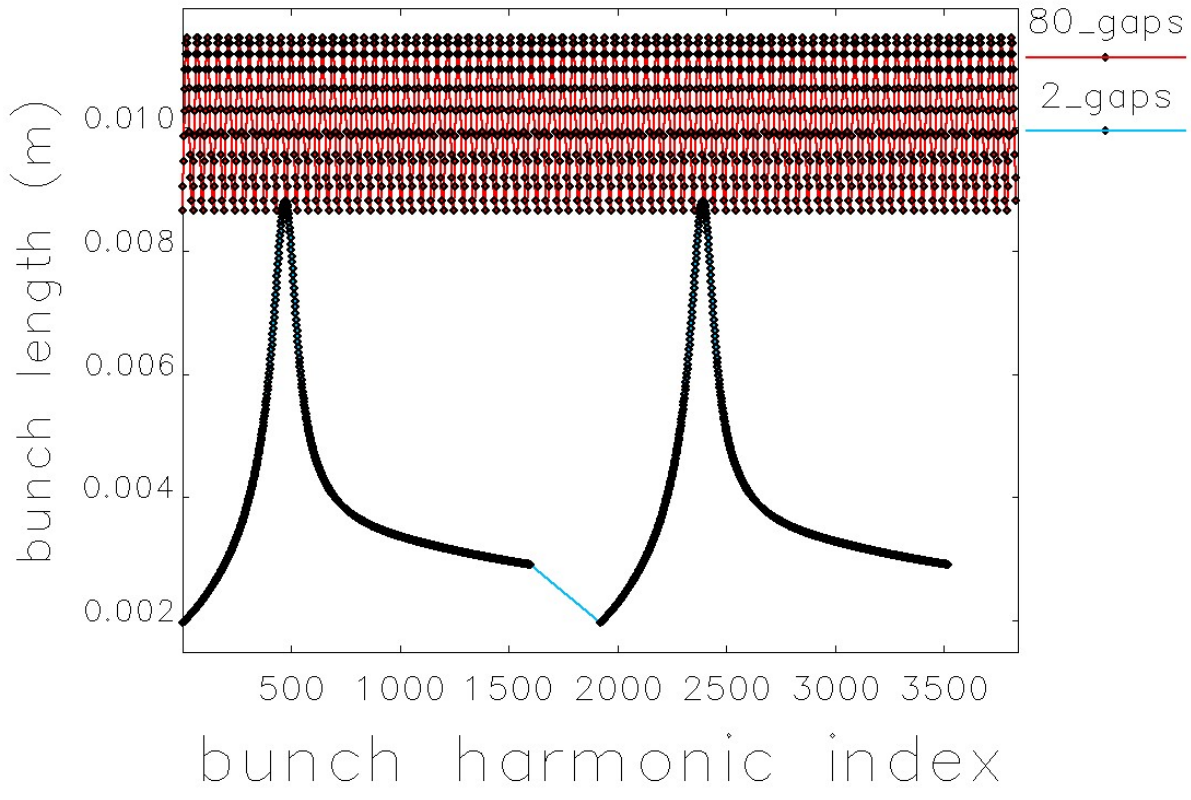
Bunch Length

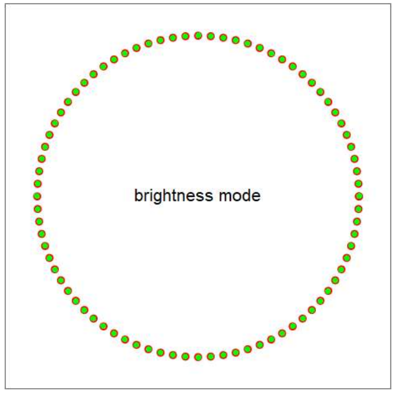


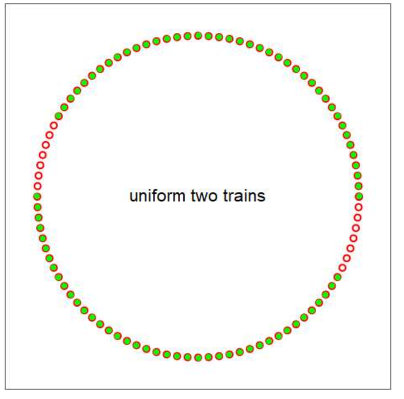
Transient beam loading @ brightness mode

- Nominal brightness filling pattern: 3840 = 80 * (20*2 +8)
- Long gaps filling pattern: 3840 = 2 * (800*2 +320)

- Long gaps significantly modulates the cavity voltages over the trains, leading to a significant bunch-by-bunch length variation

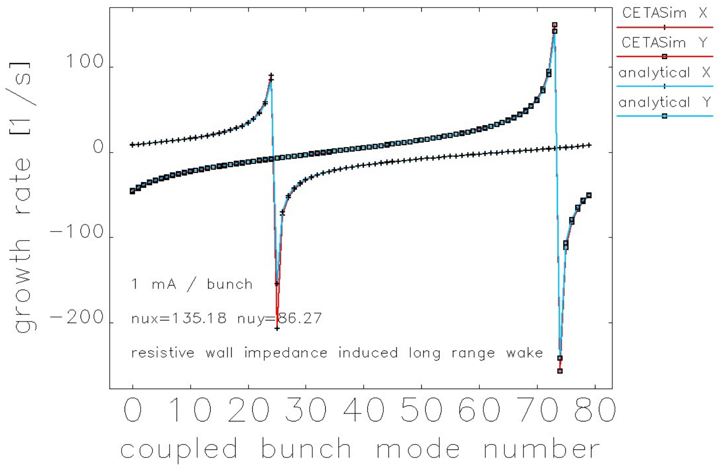


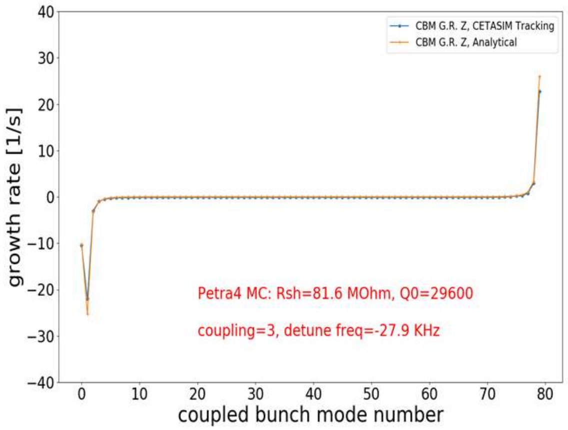


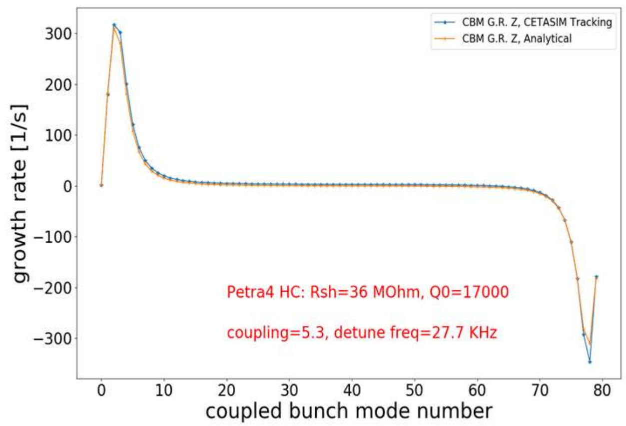


Coupled bunch simulation in CETASIM

- In general, HOMs and RW are two main sources for coupled bunch instability
- Subroutines in CETASIM are developing to simulate the coupled bunch instability in general.
- Right now, with rigid bunch model, the result from CETASIM agree well with analytical production.
- Coupled bunch mode growth rate due to the RW impedance in transverse and fundamental mode of MC and HC in longitudinal.
- Still moving on…







Summary

- **In Petra4, the impedance data base is established**
- **Single bunch collective effect (Double RF system)**
  - **Longitudinal microwave instability is around 0.8mA.**
  - **Transverse single bunch current limit is 3 mA when the chromaticity is set to 5. The threshold will be reduced to 1.6mA if impedance is increased by a factor of 2.**
  - **Without errors, beam life-time is 20 hours (coupling 0.2) at 1mA. With errors up to 5% beta beating, life-time would decrease to 8 hours.**
- **Coupled bunch instability.**
  - **At the nominal chromaticity (5,5), a 100 turns or stronger feedback stabilize the transverse motion for both brightness mode and timing mode.**
  - **HOMS are will damped by HOM couplers.**
  - **With APSU ion species, the beam-ion instability roughly takes place in the range of (10,70) mA with the maximum growth rate around 450 turns, can be handled by the feedback.**
  - **Long gaps filling scheme does not help too much to mitigate the beam-ion effect in our case, (one turn "fast-ion" is strong enough).**
  - **In brightness mode, bunch length varies from (20ps to 32ps) in one bunch train due to the transient beam loading from the fundamental mode of cavities (coupled bunch instabilities are not excited in simulation)**
  - **Whereas long gaps shows huge influence on bunch length variation due to the transient beam loading. Would be better to keep filling pattern as it is in brightness mode.**
- **Inhouse code developing and benchmarking…**

Thanks for your attention!
Questions and comments are warmly welcomed!