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Task 4.3:

Vacuum Chamber Impedances and Beam Instabilities

Mikhail Zobov (INFN LNF) for Task 4.3 participants

EURIZON Annual Meeting 2023
9 February 2023

Task 4.3 Participants

CREMLINplus period

1. Yong-Chul Chae (DESY)
2. Li Chao (DESY)
3. Vladimir Raschikov (KI)
4. Sergey Matsievskiy (KI)
5. Mikhail Zobov (INFN)
6. Shalva Bilanishvili (INFN) (15/12/2021)

EURIZON period

1. Yong-Chul Chae (DESY)
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3. Mikhail Zobov (LNF INFN)
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Task 4.3 (CREMLINplus period):

Vacuum Chamber Impedances, Beam-Chamber Interaction, Instabilities

Brief Description

The interaction of the high-brightness beam with the vacuum chamber components and beam instabilities play a key role in the attempt to achieve pm-range emittances in the synchrotron light sources. The nonlinear beam dynamics will be studied to define the beam intensity limit. We plan to perform analytical and numerical studies, to evaluate beam life-time, to investigate single bunch and bunch-to-bunch instabilities as well as other current-dependent effects.

Deliverables

D4.5. Studies and optimization of USSR vacuum chambers including impedances, lifetime, intro-beam instabilities, bunch-to-bunch instabilities and other non-linear effects (M24)

D4.11 Scientific report on nonlinear effects in the USSR (M48)

Nearest Milestone

MS4.1. Conceptual development of USSR main ring, injection scheme, RF system for rings. First decisions made (M12)

Task 4.3 (EURIZON period):

Vacuum Chamber Impedances and Beam Instabilities

Brief Description (from the project amendment)

In the 4th generation light sources with extremely small emittances and very small momentum compaction factors it is very important to preserve beam parameters as provided by the lattice original design. In the real operation of the storage rings for the user run, many different bunch fill patterns with different beam and bunch intensities were envisioned in the light sources in operation as well as in the light sources on the horizon across Europe. The fill patterns need careful study of collective effects to control the bunch motions and beam quality which will ultimately determine the performance of the light sources. In this regard Task 4.3 will study the impact of RF cavities and the ring impedances on the beam dynamics by focusing on two areas. One is to develop the suite of software as a scientific tool to investigate the single-bunch and multi-bunch instabilities, the effect of bunch-by-bunch feedback systems, the high current beam-loading, and to evaluate the ion effects for arbitrary fill patterns. The other is to design some key vacuum chamber and hardware components, such as RF cavities, BPMs, bellows etc., with aim to minimize their beam coupling impedance driving the beam instabilities. At the end of the project**, it is planned to deliver 1) the software CETA (Collective Effect Tool Analysis) for use by the European light source community and its scientific report produced by using CETA applied on PETRA-4 as a specific example, and 2) a report describing possible design solutions of the vacuum chamber components which can help reducing the beam impedance and which can eventually be adapted also to other synchrotron light sources.**

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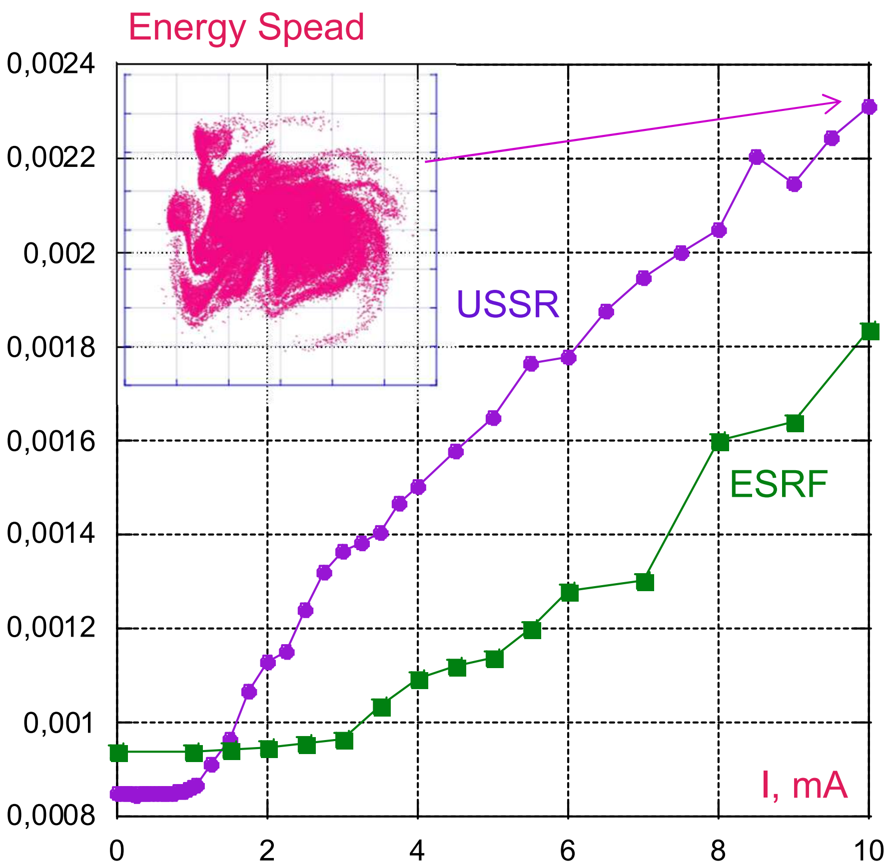
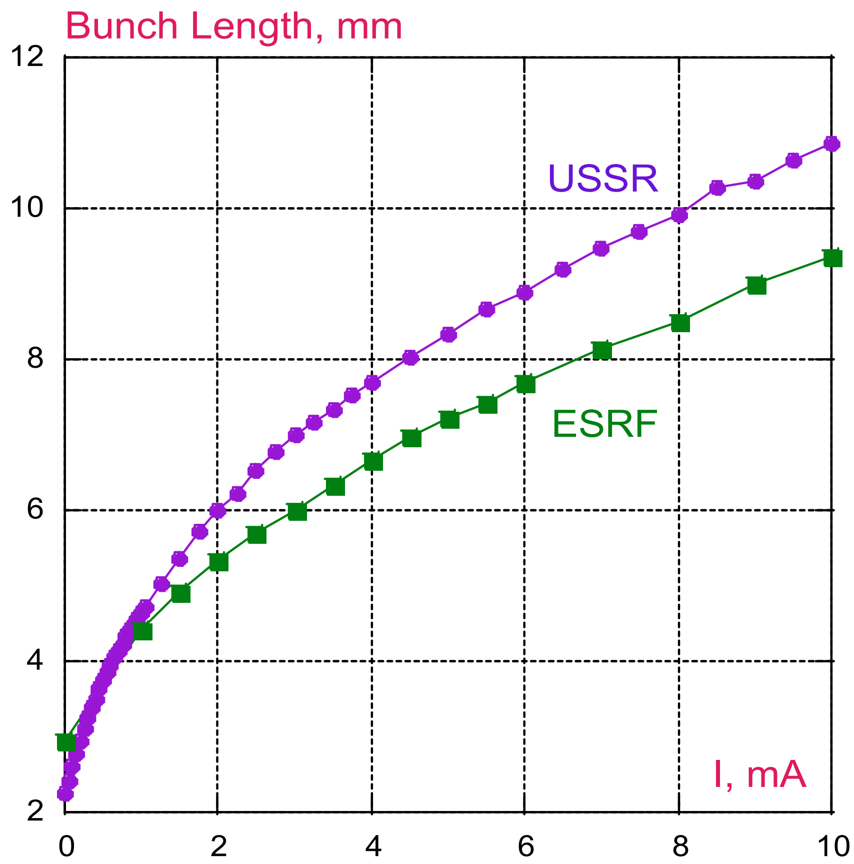
Bunch Energy Spread and Bunch Length in ESRF and USSR



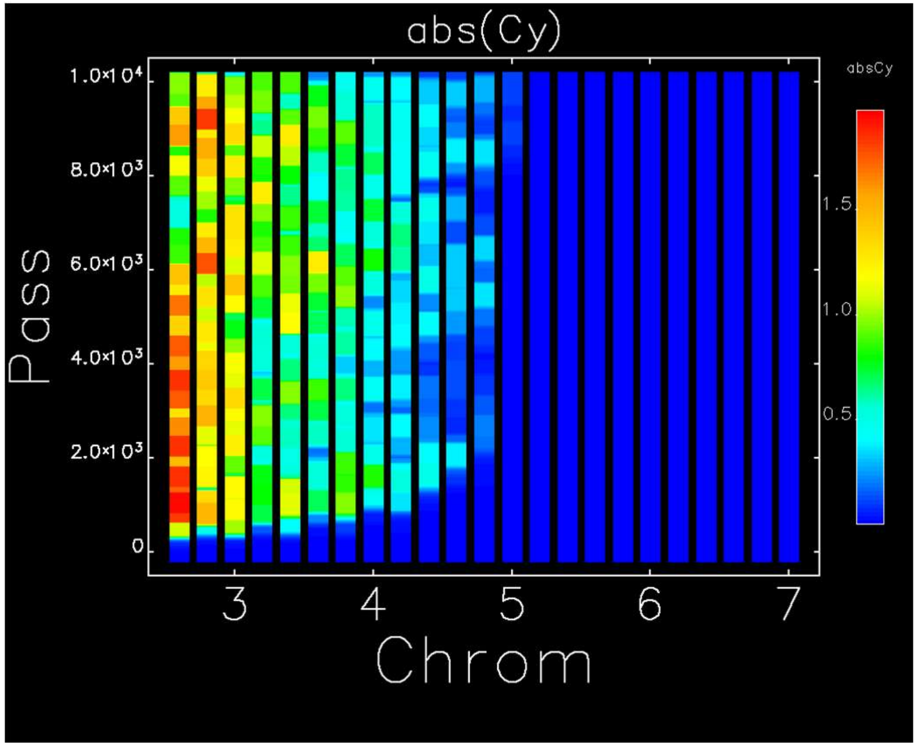


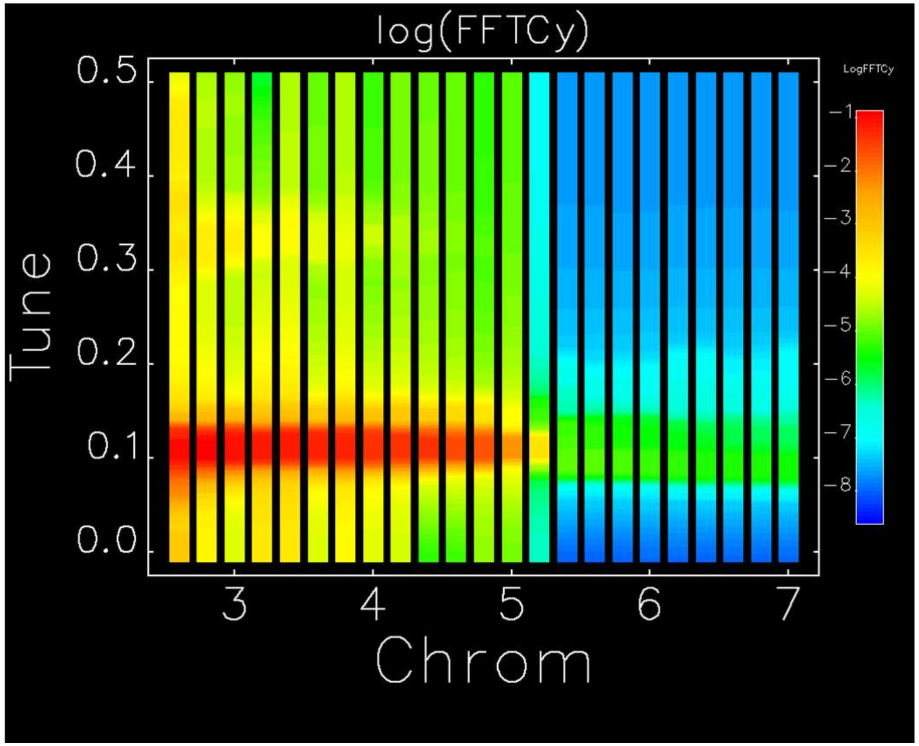
We thank Task 4.1 participants, especially ESRF group members, for providing ESRF impedance model and help in benchmarking the simulation codes

Vertical Beam Motion and Chromaticity

- Limiting apertures were removed from the simulation.
- Recored the vertical bunch center motion and presented in the heat map.
- Increasing chromaticity reduces the bunch center motion.

<u>Current = 5.0 mA</u>





USSR Modes of Operation and Beam Parameters

- Harmonic number = 1240
- Coupling ey/ex=0.03

Parameter	Reference	Brightness Mode	Timing Mode
Total Current (mA)		200	200
Number of Bunches		620	40
Bunch Current I_b (mA)	0.01	0.325	5.0
Hor. Emittance ε_x (pm)	68.2	85.7	123.2
Ver. Emittance ε_y (pm)	2.0	2.6	3.7
Bunch Length σ_t (ps)	9.20	13.11	30.1
Energy Spread σ_E (10^{-3})	0.86	0.93	1.46
Touschek lifetime τ (h)	49.6	25.7	5.3

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CETA and CETASim

- Used to evaluate the beam collective effects (single bunch and coupled bunch dynamics)
- Partially applied for USSR and PETRA4 storage rings

- **Collective Effect Tool and Analysis (CETA)**
  - Developed in C++
  - Analytical formula based study and analysis
  - Impedance data can be imported from external file or generated by code itself if analytical model exists
  - Effective impedance, kick factor and loss factor simulation for single bunch
  - Haissinski Solver in longitudinal direction
  - Vlasov Solver in transverse direction (Laguerre polynomial mode decomposition in phase space)
  - Coupled bunch instabilities

- **Collective Effect Tool and Analysis by Simulation (CETASim)**
  - Developed in C++
  - First principle simulation based on lattice transfer maps
  - Multi-bunch, multi-particle per bunch and arbitrary filling pattern settings in the lattice.
  - Beam-ion simulation
    - Multi-Gas types and multi-interaction points between ions and electron beam
    - Both weak-strong and strong-strong model available
  - Bunch-By-Bunch feedback (transverse direction)
    - Take the digital FIR filter coefficient, gain, delay as input.
  - Long range wake effect simulation
    - Wake field is generated by analytical model (Resistive wall or RLC long range wakes)
  - Coupled bunch mode Drive-Damped simulation
    - Coupled bunch modes can be driven one by one and analyzed by the decomposed IQ singles
  - Transient beam loading simulation
    - Unlimited resonator modes can be set into code
    - Beam induced voltage is treated in the phasor space
    - LLRF Cavity feedback is under developing (have to switch to cavity phase state model)
  - Interaction between broad band impedance and bunch is not implemented yet.

CETA Examples

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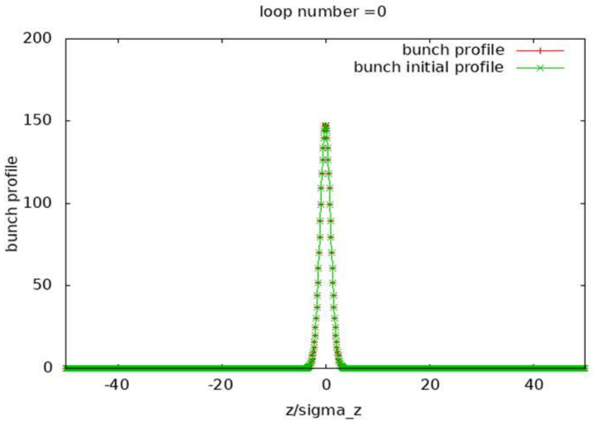
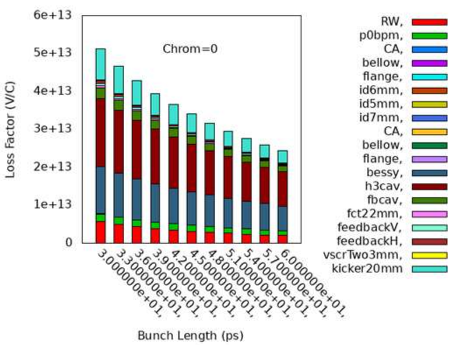
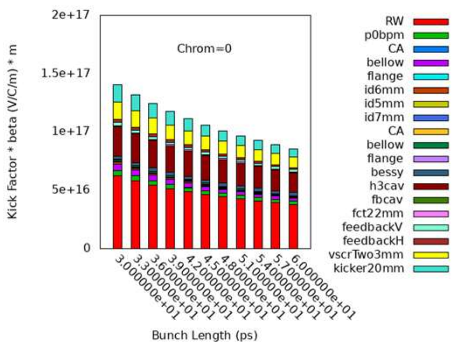
Haissinski Solver

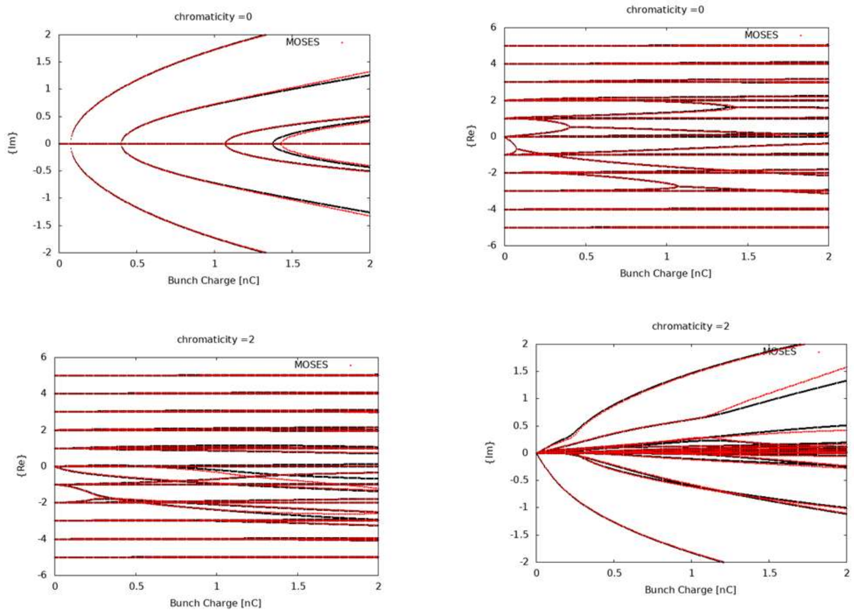


Loss and kick factor in Petra 4

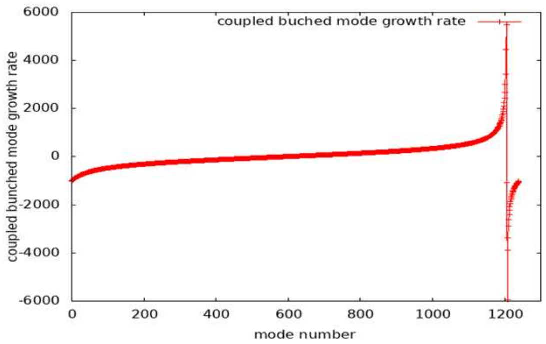




Vlasov solver (CETA/MOSE)

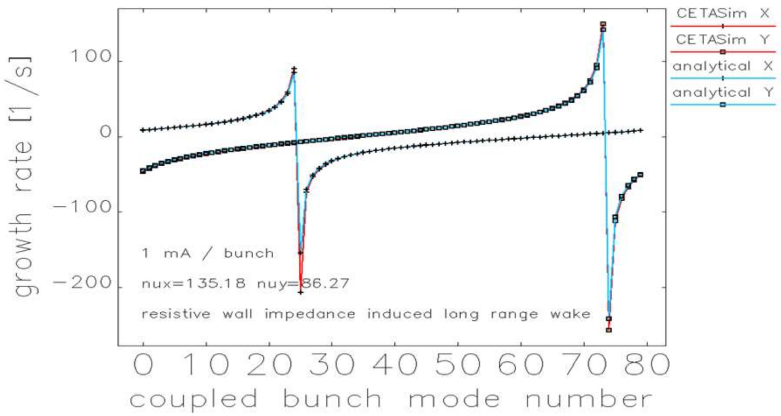


Coupled bunch growth rate

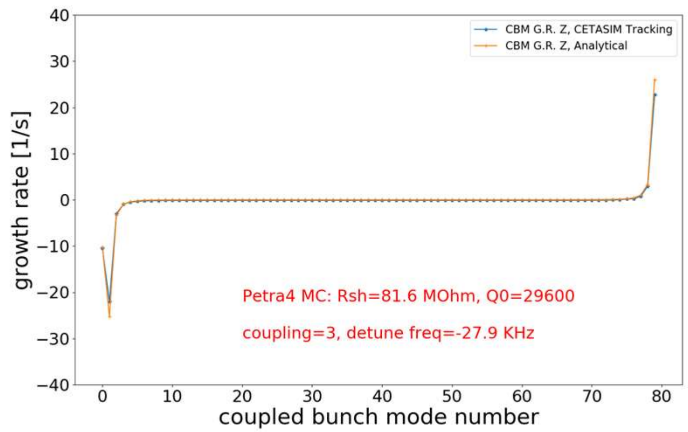


CETASim examples

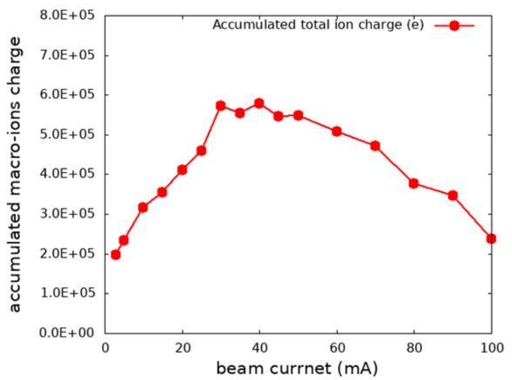
Transverse coupled bunch instability (resistive wall)



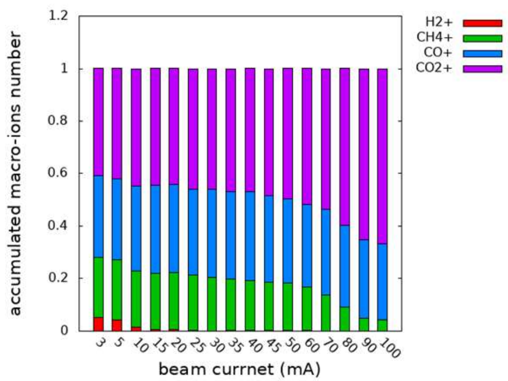
Longitudinal coupled bunch instability (RF cavity)



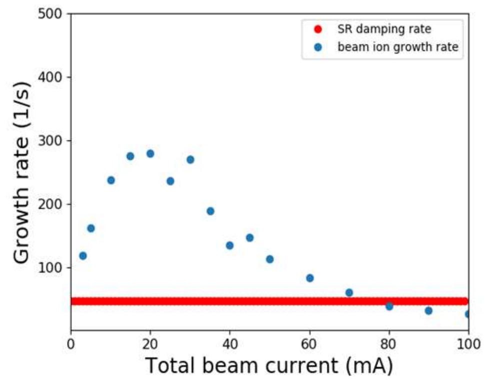
Beam-Ion effect in Petra4



Accumulated ion charge Vs current



Residual ions percentage Vs current

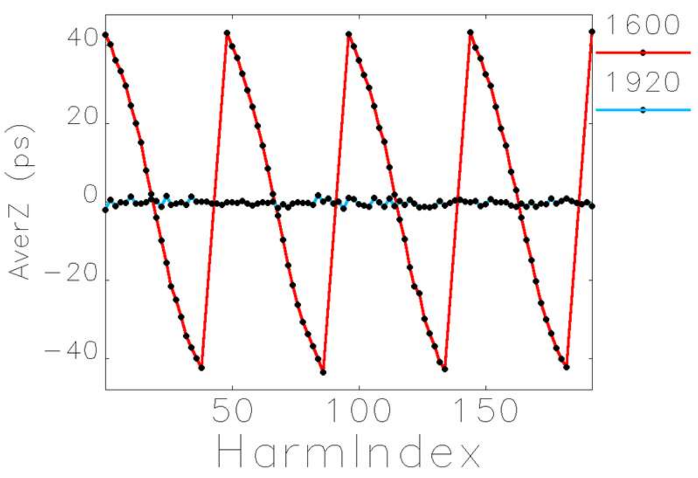


Beam-ion growth rate Vs current

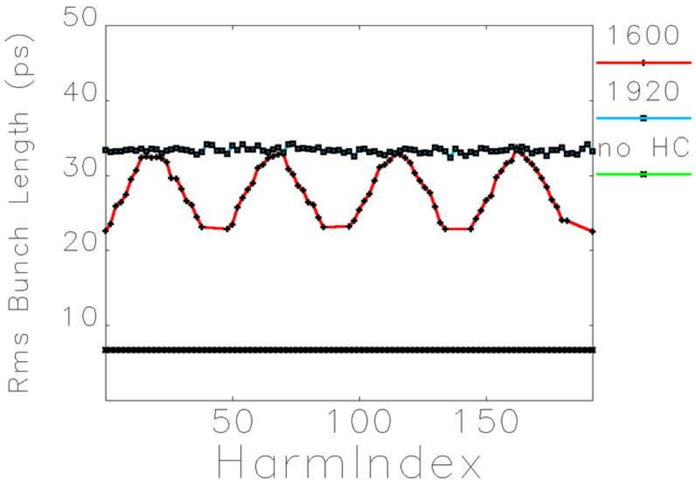
CETASim examples@Transient beam loading in PetraIV

- Transient beam loading simulation in Petra 4 (coupled bunch instability is turned off)
- MC and HC are norm conducting and active system
- harm=3840; 80 trains; 48 buckets per train, 5K macro-particle per bunch
- Case 1 (uniform 1920)
    - In each bunch train: 48 = 24*2
    - Bunch center stays around 0
    - Rms bunch length (2 mm->10mm) for all bunches
- Case 2 (non-uniform 1600)
    - 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



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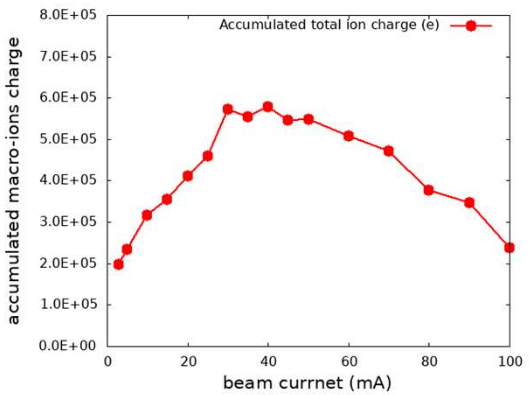
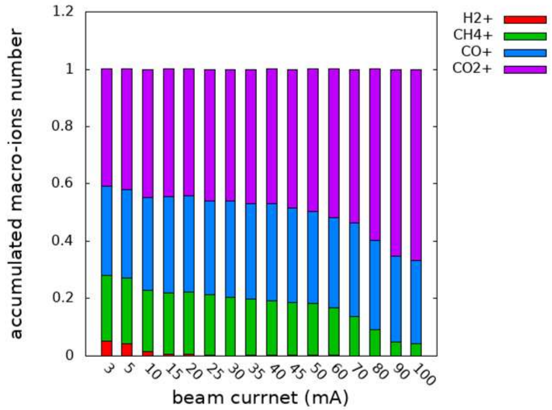
CETASim examples@Beam-ion effect in PetraIV

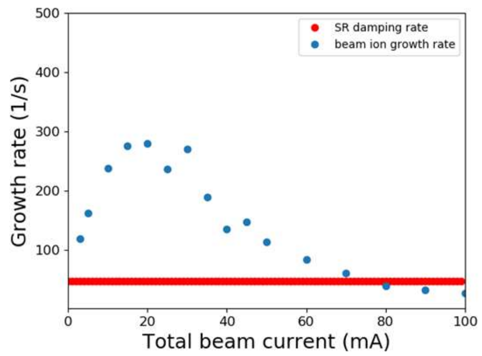
- **Beam-ion study is launched with Max-IV gas species.**
- **In low beam current region, less ions are generated per interaction.**
- **In high beam current region, more ions are generated per interaction, but more ions are over-focused and get lost also**
- **Growth rate is obtained by fitting action J within the range of (0.1,1) rms beam size.**
- **Beam ion instability takes place within 70mA**
- **Growth rate at 20 mA 300 (1/s) is around 450 turns.**
- **Beam-ion effect is very weak in timing mode.**



Total ion charge after 10K turns



Ion species ratios after 10K turns

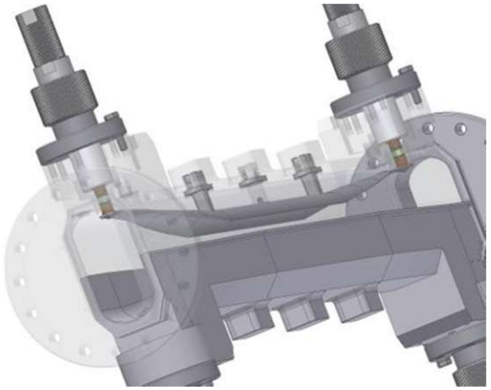


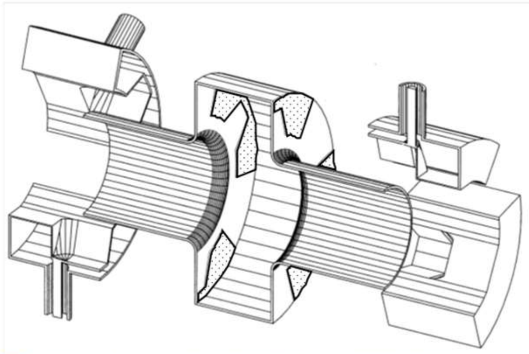
Growth rate of MaxJy

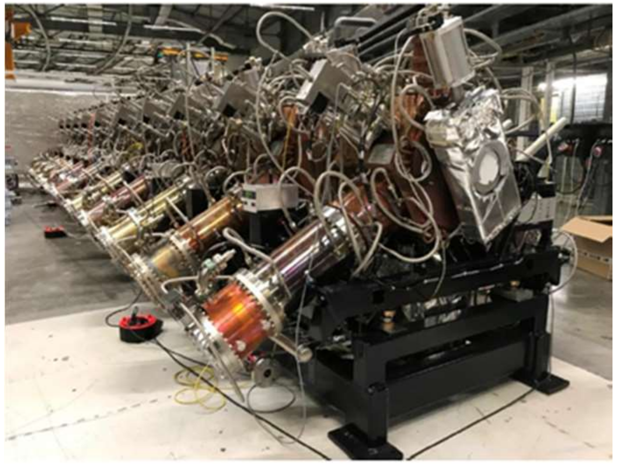
	H_2	CH_4	H_2O	CO	CO_2	**Ring**
Initial	0.43	0.08		0.36	0.13	APS-U
Initial	0.96	0.01		0.01	0.02	MAX IV

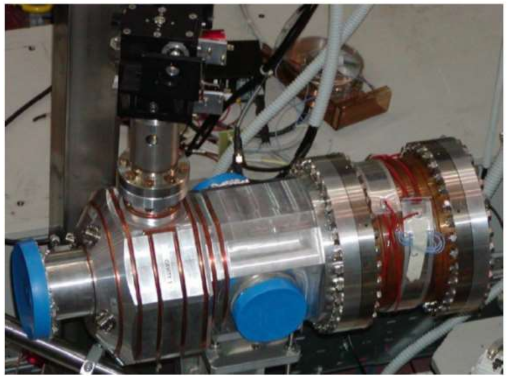
Examples of best design solutions of vacuum chamber components and hardware considered for USSR

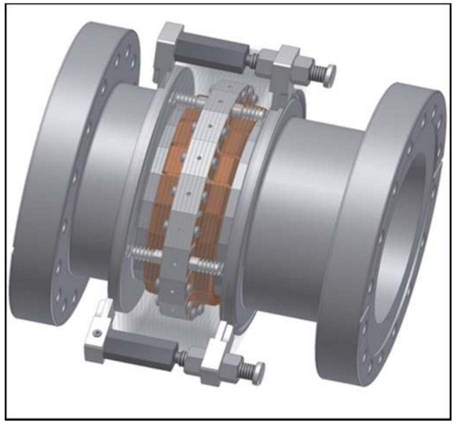
1. 500 (376) MHz HOM damped RF cavities (ESRF, BESSY, ALBA)
2. HOM damped harmonic cavities (different designs)
3. DAΦNE longitudibal feedback kicker
4. ESRF bellows adapted from DAΦNE design
5. SIRIUS conical BPMs
6. DAΦNE Injection kickers with double taper striplines
7. KEKB MO-type flanges
8. Else



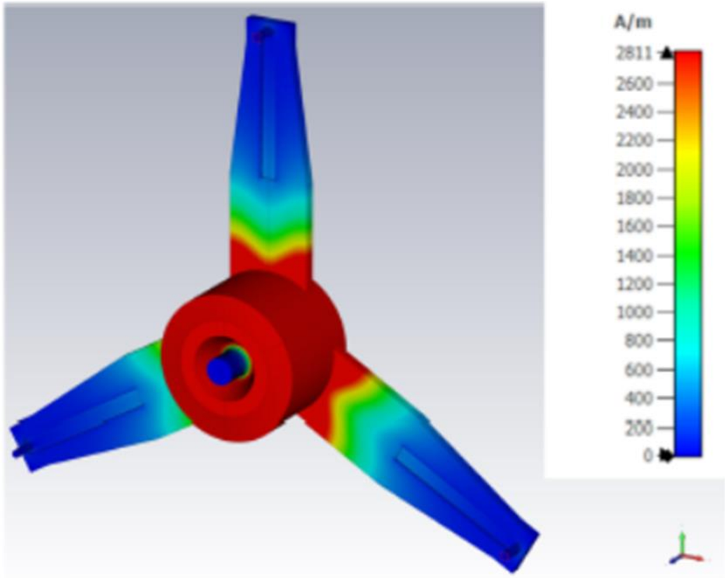


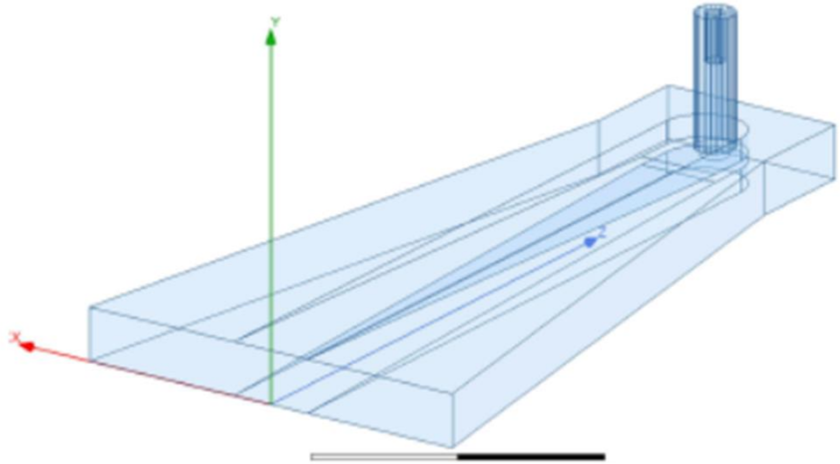






RF Cavities with Waveguide-to-Coaxial Transitions for HOM Suppression





Loaded cavity HOM properties.

Mode Freq./GHz	R/Q Ω	Undamped Q	Damped Q perp. wg
0.476	4.88	34782	260
0.817	4	47511	800
0.957	0.9	57376	500
1.004	0.7	36969	370
1.173	5	66449	360
1.223	0.9	46709	1400
1.469	2.0	51519	1300
1.501	0.8	70188	800
1.568	0.3	111994	150

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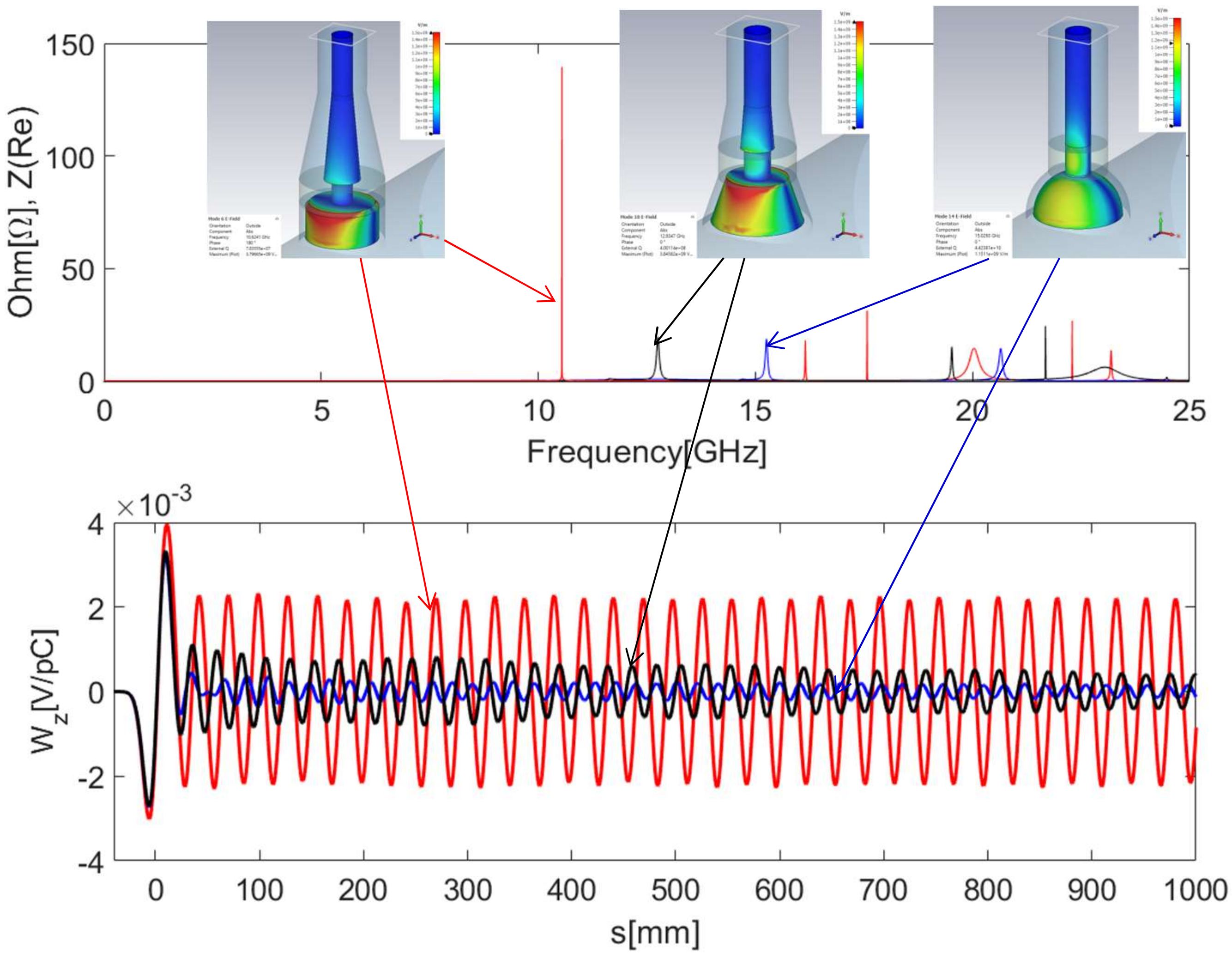
Impact of BPM Button Shape on Coupling Impedance



By optimizing the shape of the BPM button the HOM impedance can be reduced while keeping/improving the BPM signal sensitivity

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Last Milestones and Deliverables of Task 4.3

D4.3.1 (M48, INFN/DESY) Scientific report on collective effect studies and design solutions for low impedance vacuum chamber components in modern synchrotron light sources

M4.3.1 (M48, DESY) Release of a software for analytical and numerical studies of the instabilities in synchrotrons