TRIUMF EIC PARTNERSHIP WORKSHOP

26-29 October 2021

Collective effects at ESRF

S. White

Thanks to L. Carver and T. Brochard for the material and simulations

ESRF | The European Synchrotron

OUTLINE

Accelerator complex

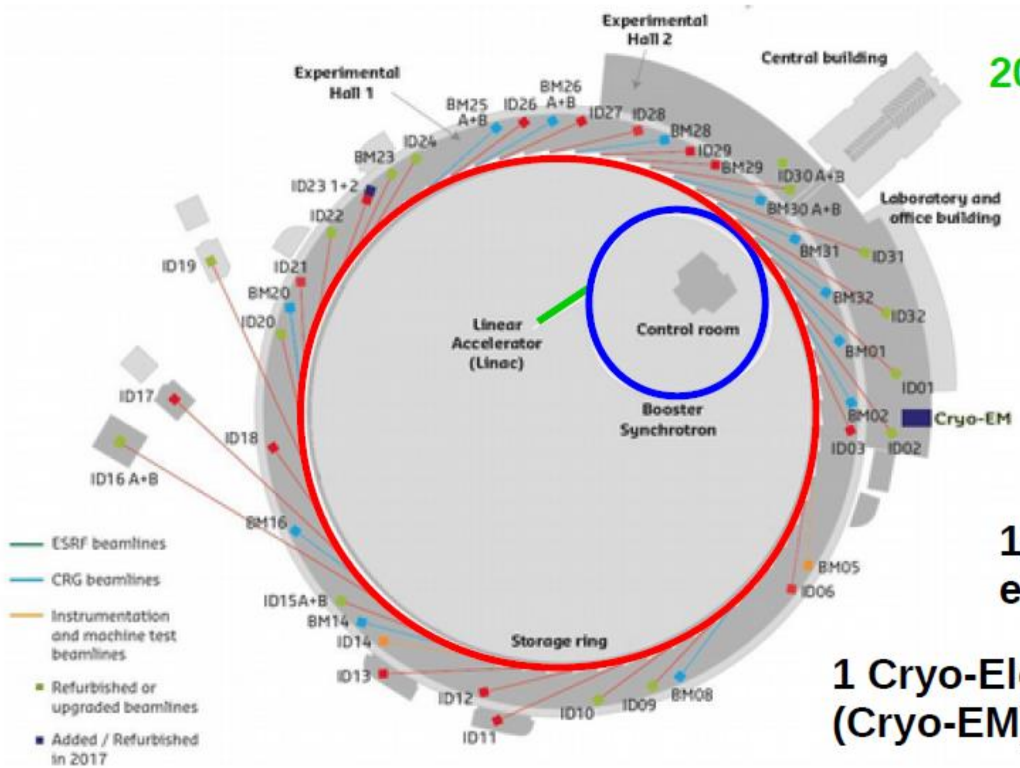
Impedance model

Model Characterization

Operation experience

Summary and outlook

ESRF ACCELERATOR COMPLEX



200 MeV Linac

6 GeV ramped Booster (300 m)

6 GeV Storage Ring (844 m)

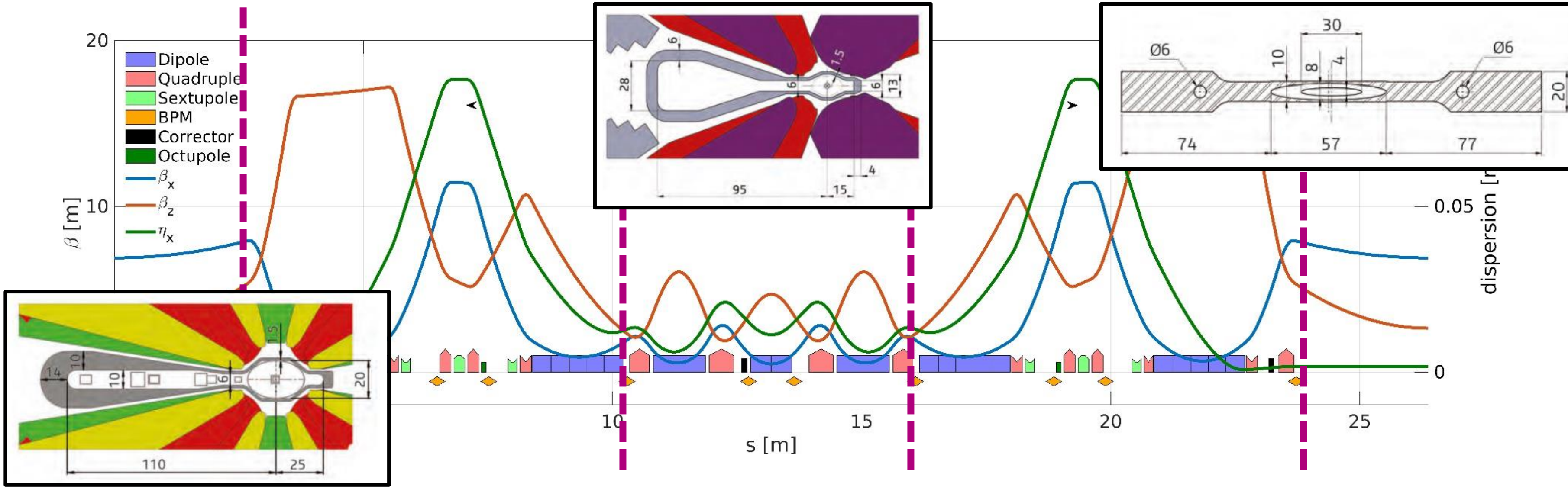
33 Insertion Device (ID) end stations

16 Bending Magnet (BM) end stations

1 Cryo-Electron Microscope (Cryo-EM)

The accelerator complex was recently upgraded to implement the HMBA lattice and achieve 130pm horizontal emittance

HMBA LATTICE



- **Reduce emittance with increased number of dipoles:**
  → strong distributed focusing and sextupoles
  → reduction of the magnets and vacuum chambers aperture (32mm → 20/13mm)
- **Increased beam coupling impedance:**
  → partially compensated by reduced β-functions
  → Dipole chambers material changed from stainless steel to aluminium

- **Careful design of the vacuum systems to minimize beam coupling impedance**

VACUUM SYSTEM DESIGN AND IMPEDANCE MODELING

A (rather) strict policy was applied in order to minimize as much as possible the beam coupling impedance of the storage ring:

- All taper angles <5 degrees
- All absorbers and vacuum pumping ports located in the antechamber
- All mechanical design seen by the beam checked by beam dynamics experts for validation
- Avoid abrupt transitions, even far of the beam axis
- Critical devices expected to contribute strongly to the impedance model carefully optimized with EM codes, several iterations with mechanical engineers often needed

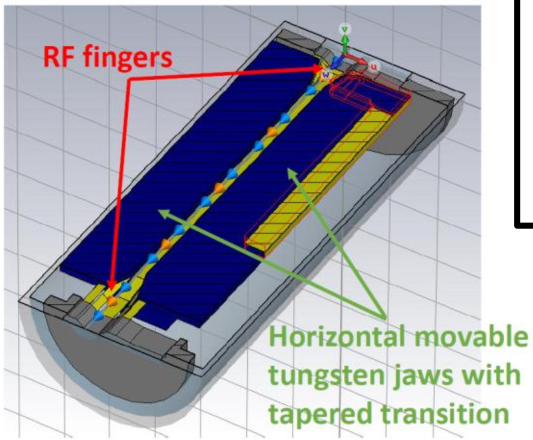
Close collaboration with mechanical engineers proved to be essential to understand limitations and find good compromises

Several simulation codes were used to build the impedance model:

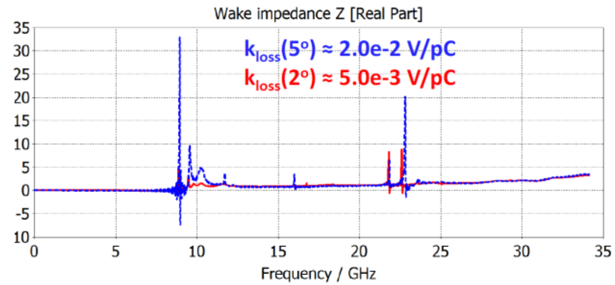
- CST particle studio mostly for optimization of the beam coupling impedance
- GDFIDL for the short range wake field: use computing cluster
- ImpedanceWake2D and CST for the resistive wall and coated chambers

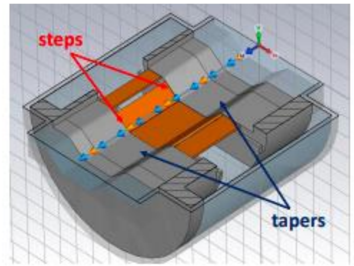
All tracking simulations were done with the impedance module of the Accelerator Toolbox: main optics design and tracking code used at ESRF with python and Matlab interface

EXAMPLES OF OPTIMIZATIONS

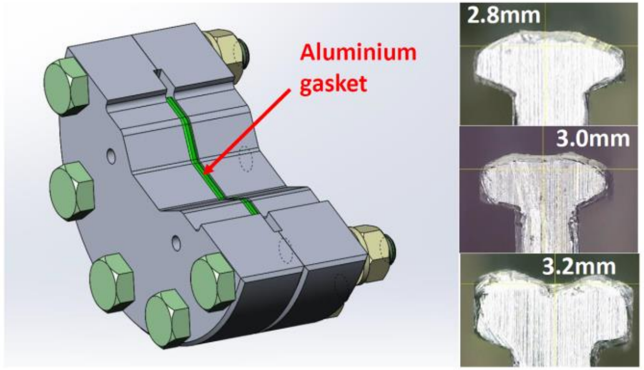


Collimator

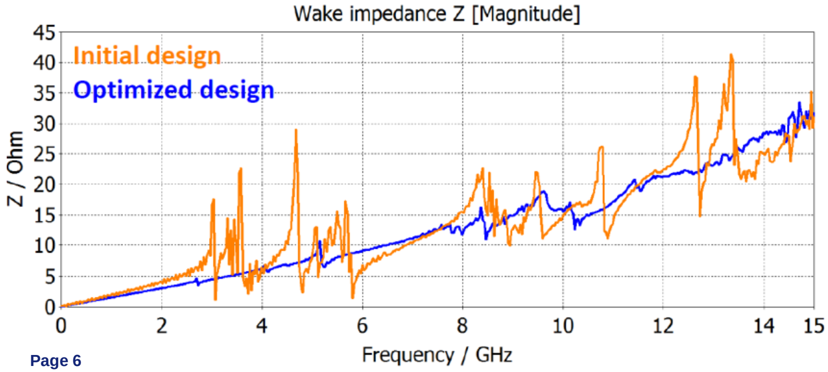


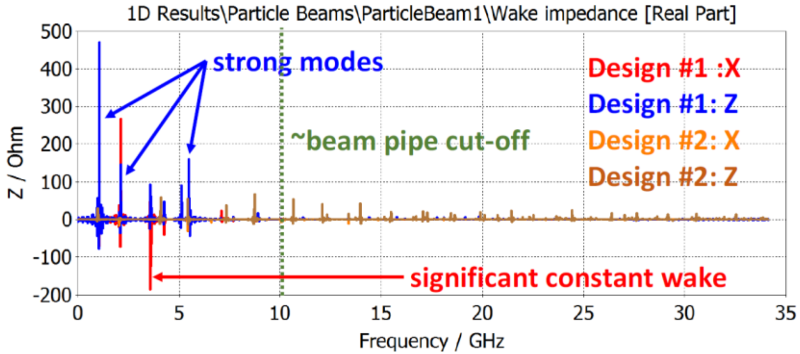


RF fingers



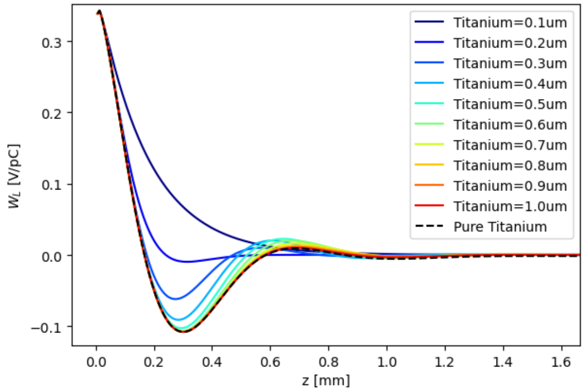
Zero impedance flanges

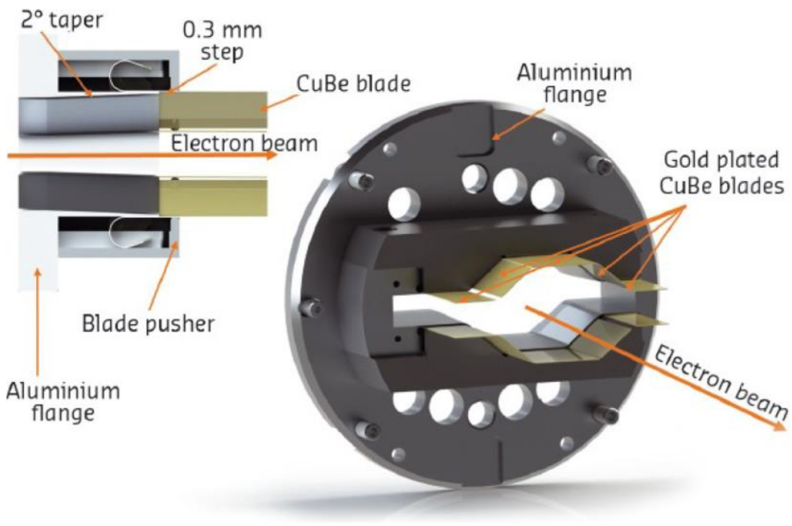




RESISTIVE WALL MODEL

- **Resistive wall impedance is modelled with CST using the real profile, benchmarked with IW2D**
- **Coated chambers (ID + ceramic) were modelled in IW2D**
- **Full machine model built from the lattice using optics and material: total length is 839.12143m**
- **Wake potentials with 1mm bunch length are generated to be added to the geometric impedance model**

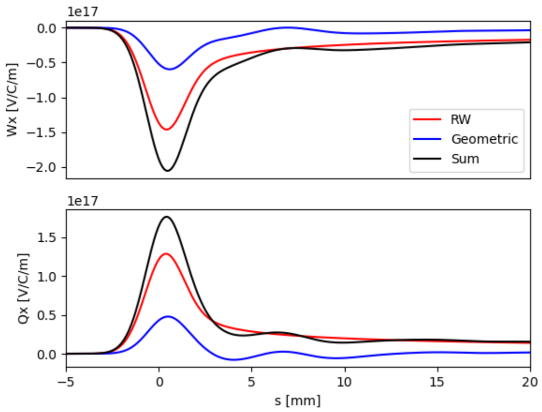


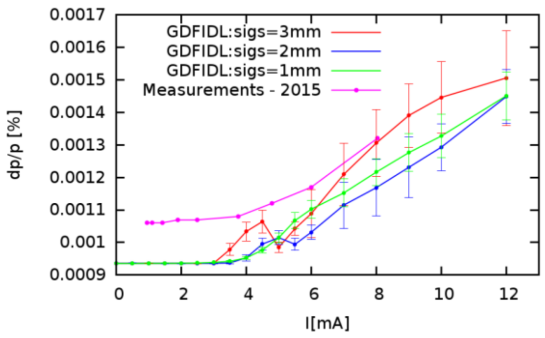


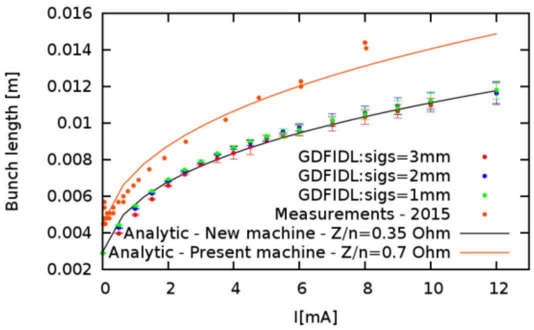
Complex ESRF chamber profile could not be modeled with IW2D: ~20% different w.r.t enclosed ellipse

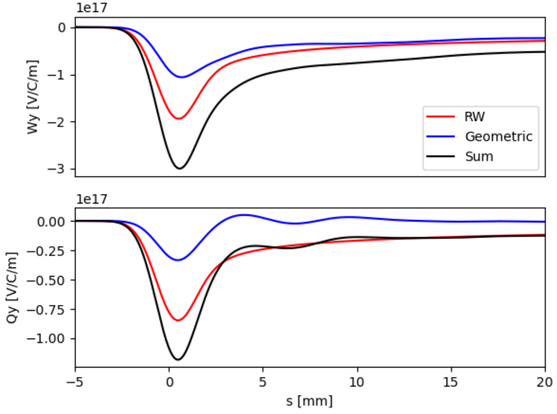
GEOMETRIC IMPEDANCE

- Geometric impedance (short range) is modelled with GDFIDL with 1mm bunch length: convergence checked with tracking simulations
- The total modeled length is 167.5064m
- The material conductivities is included: the impedance that we simulate is therefore naturally pessimistic, with 167m of the RW model included twice. Corresponds to about 10% increase in total impedance (in Z).

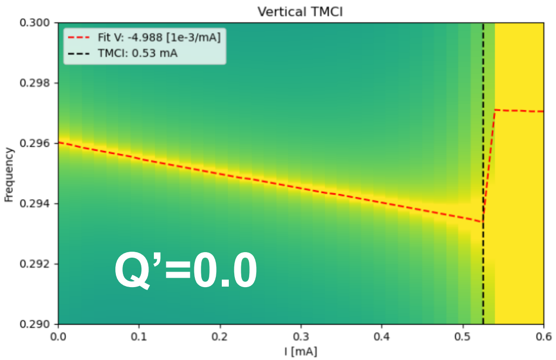


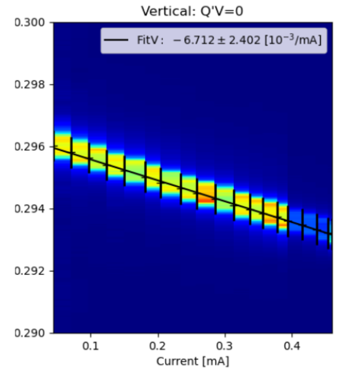


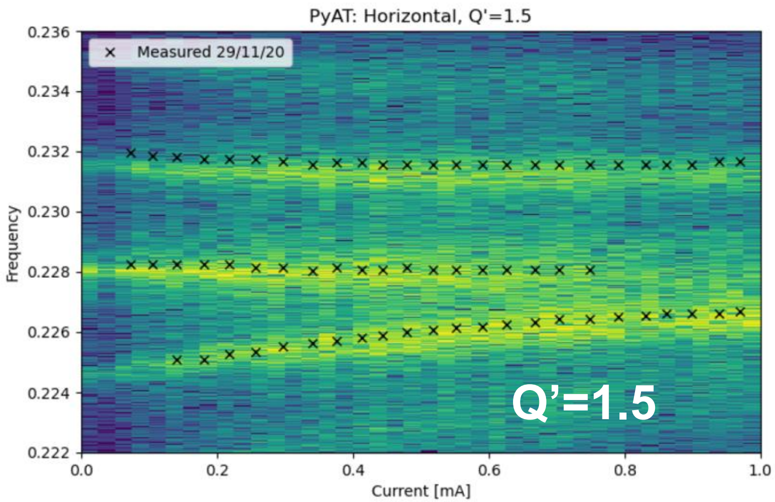




TRANSVERSE MODE COUPLING







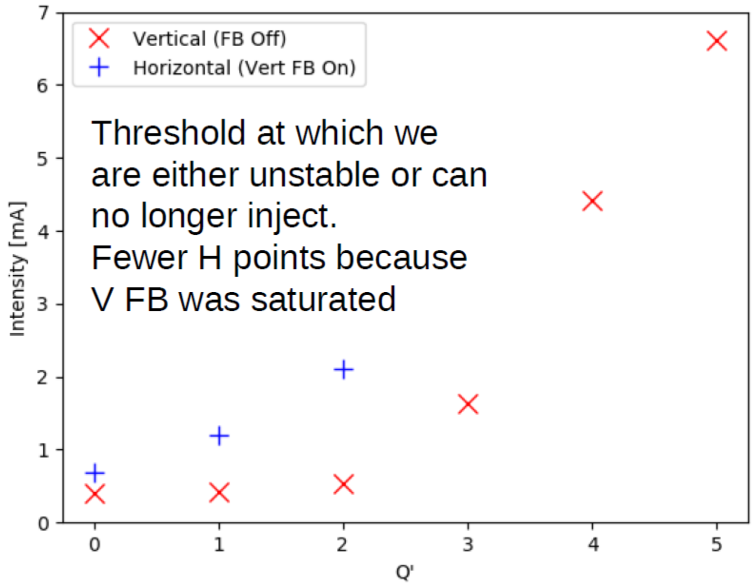
- Transverse mode coupling instability threshold measured at Q'=0 in both plane
- Use the MBF to stabilize the cross-plane
- Error bar on the tune measurement: tune fluctuations, to be confirmed
- Good agreement with model

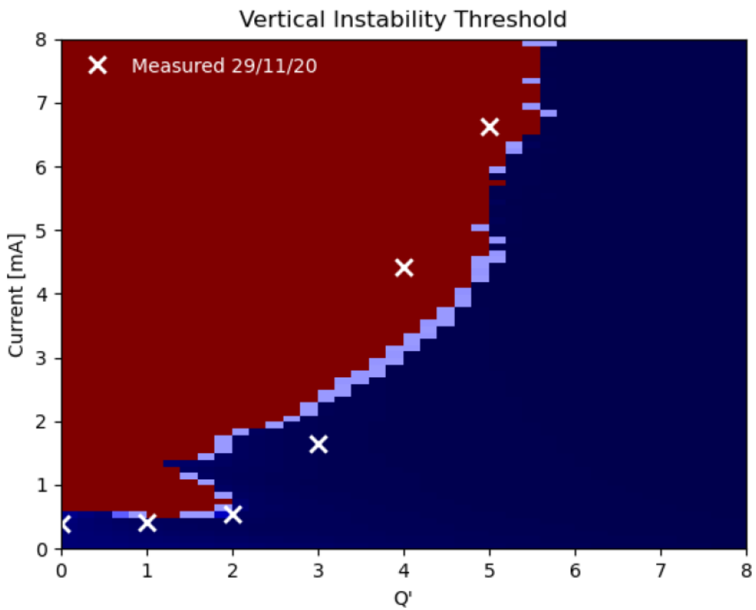
	Simulated	Measured	Units
TMCI	0.53	0.44	mA
Tune Shift V	-4.988	-6.712 ± 2.402	10^{-3}/mA
Tune Shift H	-0.501	-1.082 ± 2.402	10^{-3}/mA

HEADTAIL INSTABILITY THRESHOLD

- **The transverse instability threshold chromaticity and impact of MBF were measured:**
  - Effect of feedback not verified in simulation
  - Good agreement without feedback

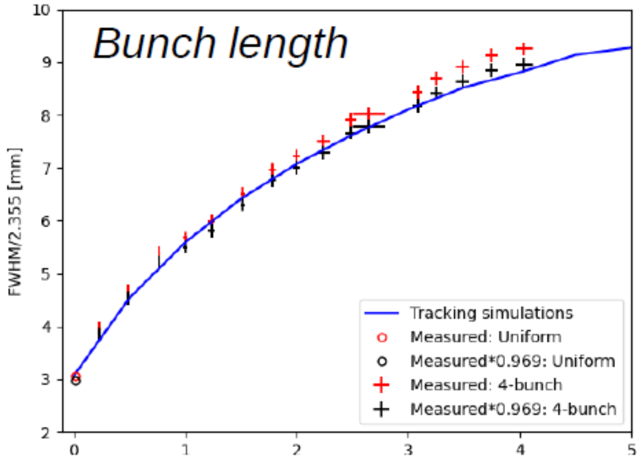
- **Nominal single bunch current of 10mA could be achieved with either Q'~10 or MBF: the present strategy is to optimize Q' for lifetime**

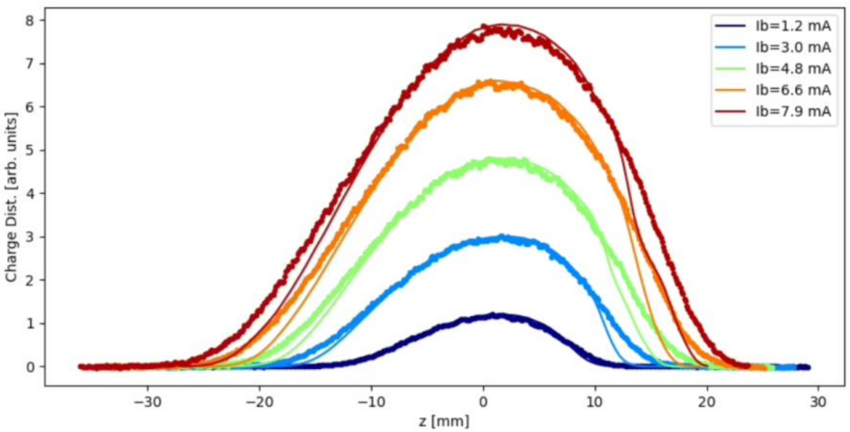


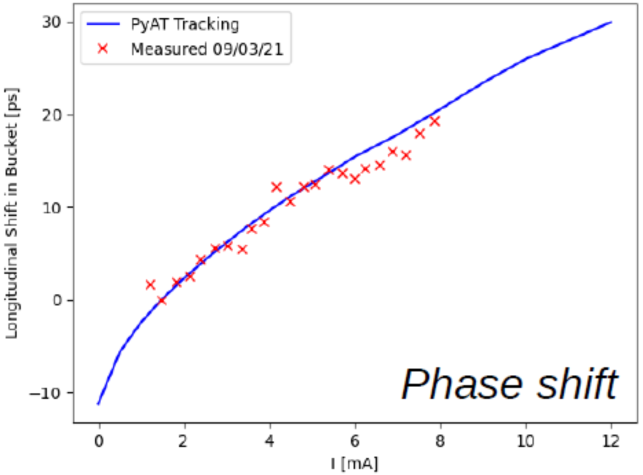


STREAK CAMERA MEASUREMENTS

- **The streak camera give access to two quantities:**
  - Bunch length measurement versus current: Z/n
  - Phase shift versus current: loss factor
- **Very good agreement for both measurements**
- **Details of the profile show discrepancies with respect to simulations**
- **Effects of ID gaps negligible**

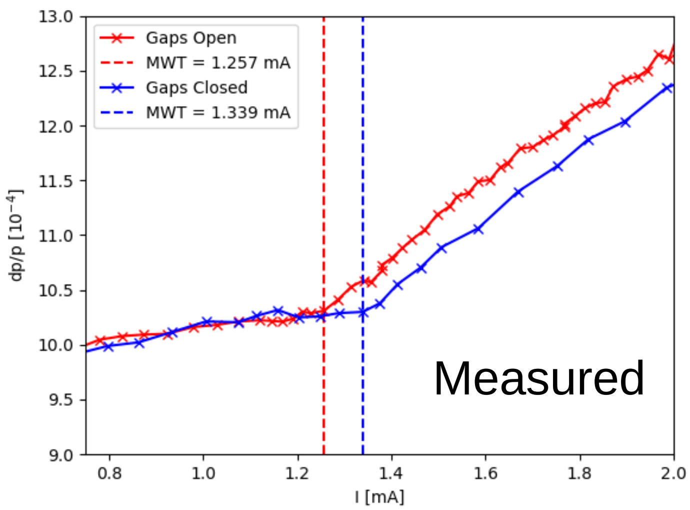


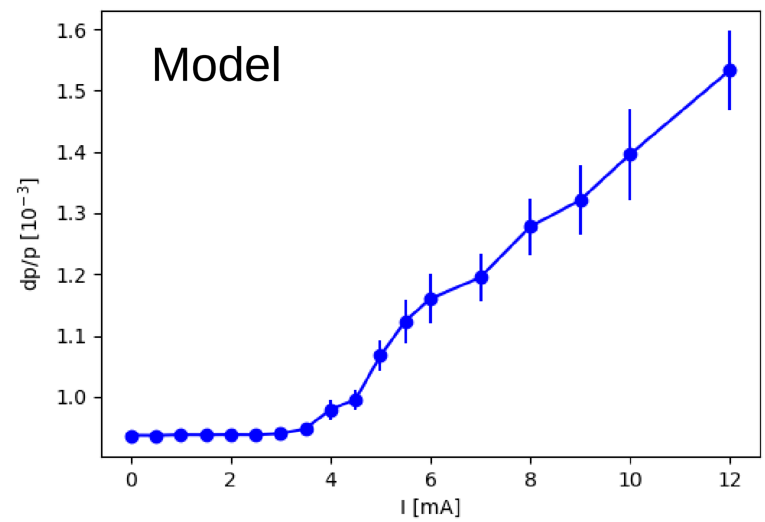




MICROWAVE INSTABILITY THRESHOLD

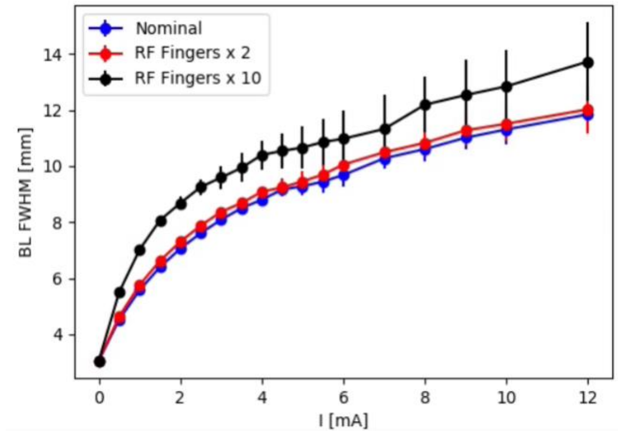
- The energy spread is reconstructed by combining 2 beam size measurements at locations with difference dispersion
- The measured MWI threshold was found to be 1.34mA gaps closed and 1.26 mA gaps open while the model predicts 3-3.5mA
- Over a factor 2 difference: model needs to be refined, small imperfection and few devices not yet included

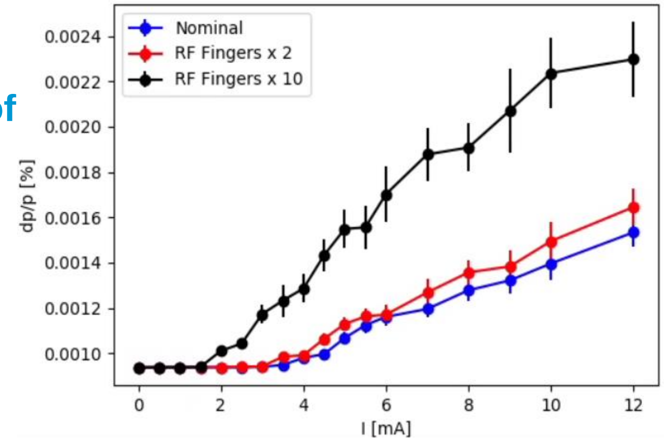


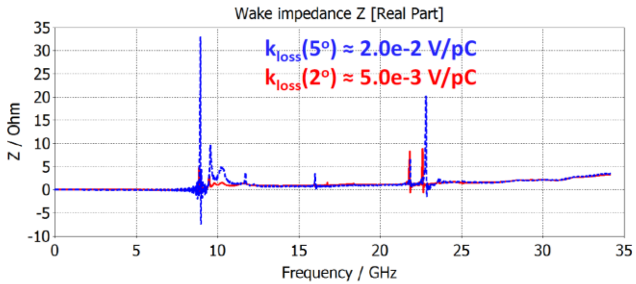


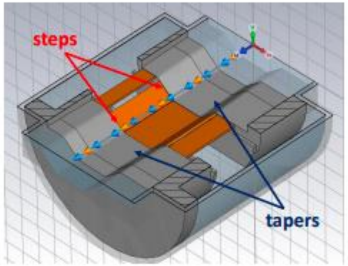
IMPORTANCE OF SMALL DEFECTS?

- As the chamber dimensions are reducing we may start to be sensitive to small defect such as:
  - Welding meniscus
  - Flanges adjustments
- These defects have been estimated to be of the order of 300μm. They are not included in the model but are present in large numbers (~ 750 just for bellows and flanges + numerous chambers welded out of several pieces)
- As a test we just scaled up the number of RF fingers (250) that feature two 300μm steps
- A better model is under construction: may explain some of the discrepancies

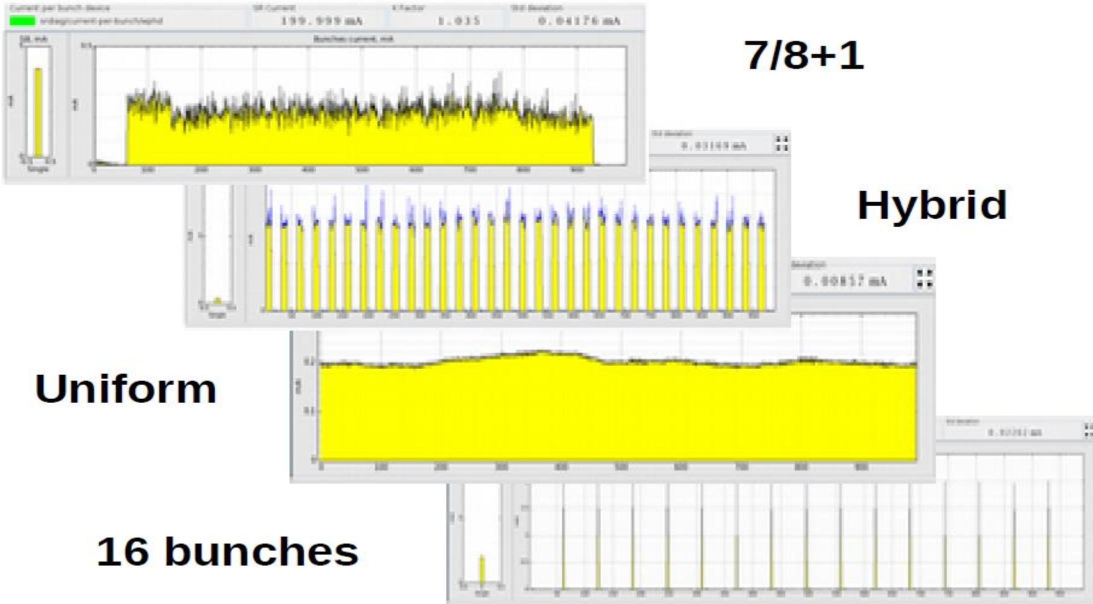






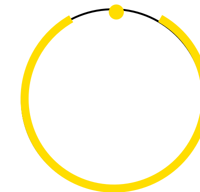


OPERATION FILLING MODES

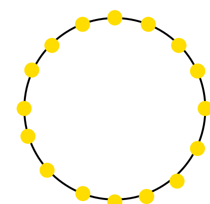


Uniform:
992 bunches
200mA total

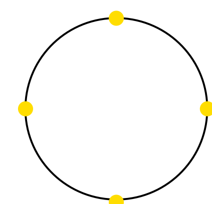
7/8+1:
868+1 bunches
200mA total
8mA single



16 bunches:
90mA total
~6mA per bunch



4 bunches:
40mA total
10mA per bunch



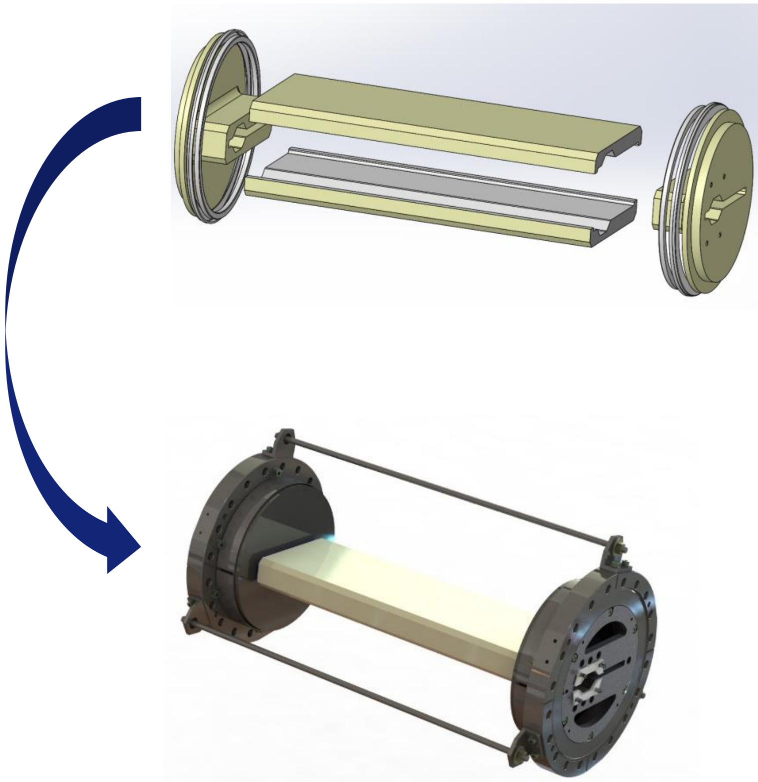
We are presently not limited by stability issues:

- We are running the machine in all modes using the optimum Q’ for lifetime ~(10,7)
- The MBF is not used in operation

Nominal bunch current of 10mA easily achieved with either slightly larger Q’ or using the MBF

Stability conditions required for a large variety of configurations

ISSUES: CERAMIC CHAMBERS



Due to the complex shape of the vacuum chamber the ceramic chamber could not be built in a single ceramic piece:

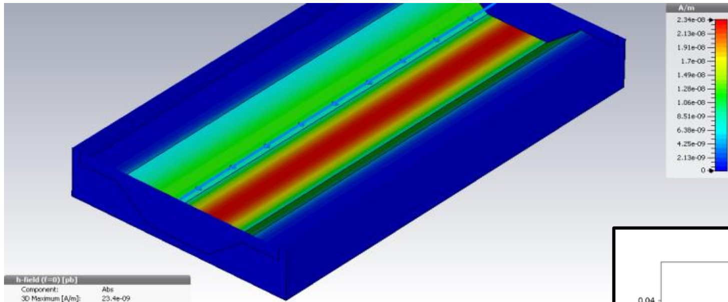
- Instead 4 piece of ceramic were used
- Later “glazed” together

Problem: when ramping the current to 90mA for the first time in 16 bunch filling mode (4.5mA/bunch) one ceramic chamber cracked at the glazing location

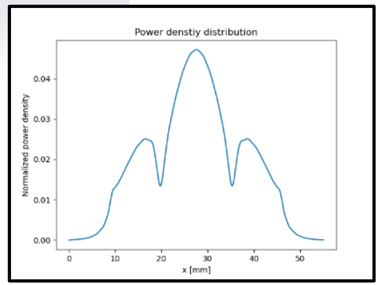
Since then we have applied limits on current for some modes:

- single of the 7/8+1 4mA (8mA)
- hybrid 150mA (200mA)
- 16b 32mA (92mA)
- 4b 16 mA (40 mA)

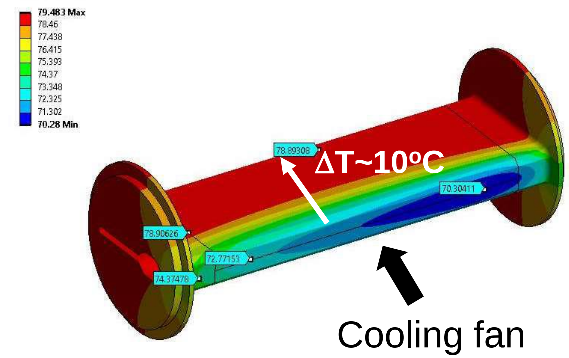
MECHANICAL WEAKNESS?



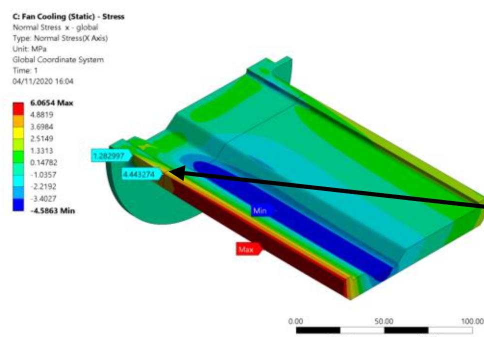
The image current density and total power deposited were computed using CST/IW2D for the full current 16 bunches beam

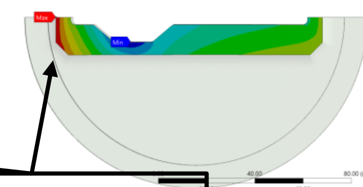


Power distribution used in Ansys for thermal simulation



The chamber asymmetry and cooling fans introduce a temperature gradient and mechanical stress on the chamber



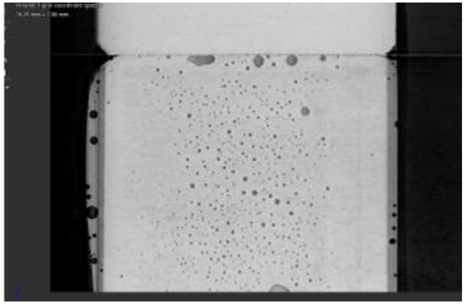


The values obtained are to low to explain the crack for an ideal chamber

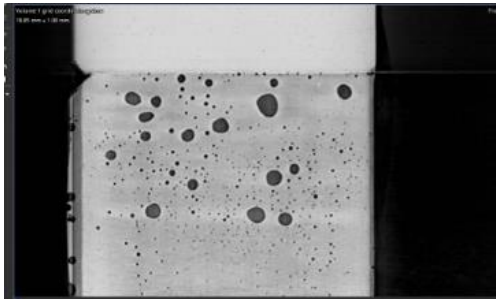
→ **Weakness in the glazing?**

INSPECTING THE GLAZING

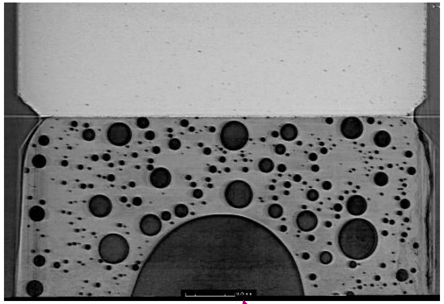
spare shaker



spare kicker



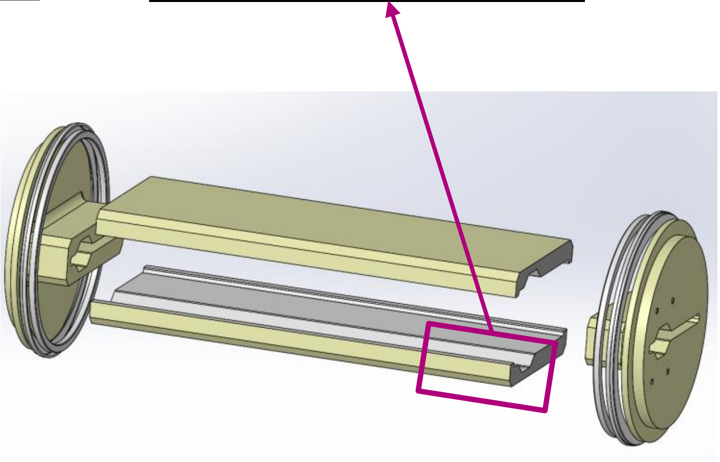
broken kicker



Air bubbles in the glazing were clearly identified and appear to be larger on the broken chamber: this can happen if the glazing reaches boiling point during the thermal cycle

Corrective actions:

- **procurement of new chambers with a ceramic body in one piece ongoing: delays, complicated manufacturing**
- **increase coating thickness: achieve nominal current at constant power deposition**



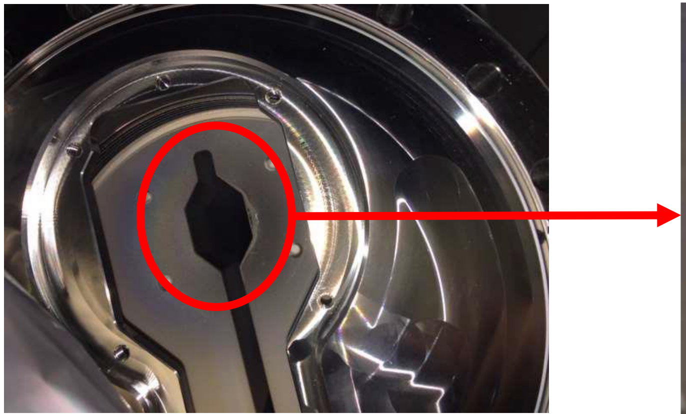
Ceramic chambers measurements done at BM05 beam line (Image courtesy of P. Tafforeau)

ION INSTABILITIES

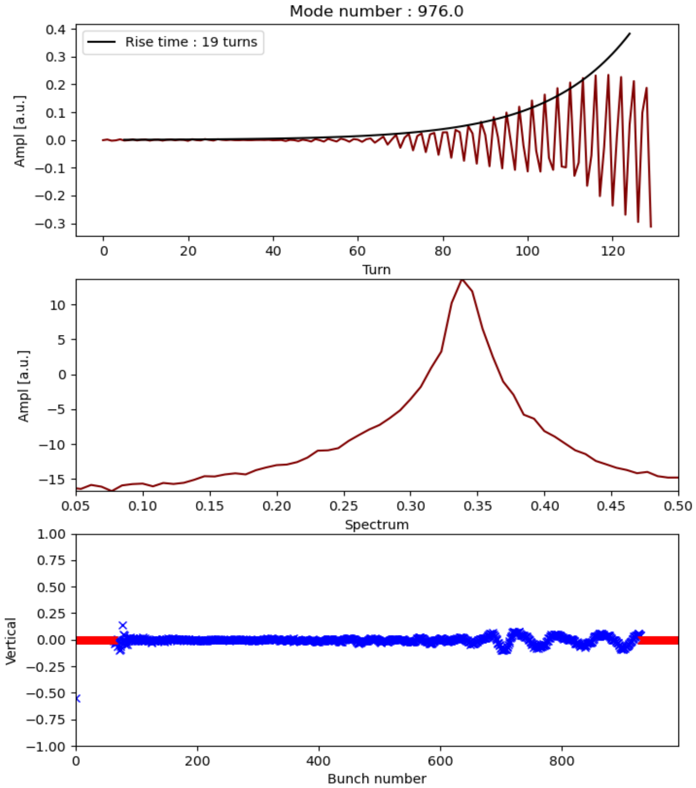
Ions instability are generally not an issue at ESRF, they were nevertheless observed in 2 occasions:

- Uniform filling after a maintenance period: results in emittance blow-up, cured with MBF and/or larger Q'
- During the commissioning: fast ion instabilities during injection causing partial or total beam loss

→ Fast ion instabilities were attributed to a loss of continuity between the ceramic and metallic flanges
→ Sparking and vaporization of the Ti coating suspected: solved with improved contact (integrated in new design)



Fast ion instability



SUMMARY AND OUTLOOK

Impedance modeling:

- Reduced aperture: enhanced beam coupling impedance
- impedance minimization in close collaboration with mechanical engineers essential

→ **able to maintain relatively similar instability thresholds w.r.t previous machine**

Impedance characterization:

- Single bunch measurement consistent with model prediction
- Discrepancy in MWI threshold

→ **small defects may partially explain the differences: study ongoing**

Ceramic chambers:

- We cracked an injection kicker chamber when ramping the current in 16 bunch
- Current in few bunch limited
- The issue is most likely related to weaknesses in the mechanical design

→ **increase coating thickness on present chambers**

→ **procure new chambers with more robust design**

Future developments (not exhaustive):

- 4^{th} harmonic cavities are under development to improve lifetime: beam induced heating reduced
- Optics upgrade for better matching of IVU and reduced emittance
- Upgrade of the injectors/injection systems for transparent injection with 100% efficiency
- Development of numerical tools: parallelized offline and online simulations tools using modern technics

MANY THANKS FOR YOUR ATTENTION