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BUILDING THE IMPEDANCE MODEL OF A REAL MACHINE

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Abstract

A reliable impedance model of a particle accelerator can be built by combining the beam coupling impedances of all the components. This is a necessary step to be able to evaluate the machine performance limitations, identify the main contributors in case an impedance reduction is required, and study the interaction with other mechanisms such as optics nonlinearities, transverse damper, noise, space charge, electron cloud, beam-beam (in a collider). The main phases to create a realistic impedance model, and verify it experimentally, will be reviewed, highlighting the main challenges. Some examples will be presented revealing the levels of precision of machine impedance models that have been achieved.

BEAM COUPLING IMPEDANCE?

Whether it is in colliders or in light sources, pushing the performance of modern particle accelerators involves generating brighter particle beams. Above a certain threshold that depends on the machine parameters, collective effects significantly affect beam dynamics and can lead to severe issues ranging from unwanted beam losses, heat load and outgassing to equipment damage. The beam coupling impedance (also referred to as *impedance* in the following paragraphs) is a category of these collective effects. It originates from the interaction of the electromagnetic (EM) fields generated by the beam of charged particles with its surroundings [1]. This interaction results in EM *wake fields*, which perturb trailing particles and can drive coherent beam instabilities that impose a severe limitation to increasing the beam brightness [2]. From a concept conceived 50 years ago [3], the mathematical definitions of the impedance as a function of frequency, and its Fourier transform (the wake function of a point charge as a function of the test particle distance) are provided in [1, 2].

The Lumped Impedance Assumption

One important assumption in the theory of impedance and wake fields is that the interactions of the beam EM fields within a finite-length accelerator element can be lumped into a single set of 3 wake functions $W_x(s)$, $W_y(s)$ and $W_{long}(s)$ that give kicks to trailing particles at a distance s following a source charge both along the direction of the particle motion (accelerating/decelerating kicks in the longitudinal plane z) and transversely (focusing/defocusing kicks in the horizontal and vertical planes x and y). In the frame of this assumption, the longitudinal distance between the source and test charges as well as their transverse offset is assumed to be conserved during their passage (see the example of a source bunch passing through a cavity with a vertical offset y_s and a test charge following at a distance s in Fig. 1). The integrated kick to the test charge in the longitudinal and transverse planes due to the example cavity depends on the longitudinal distance s between the source and test charge, but also on the respective transverse positions of the source and test charges (resp. y_s and 0 in this case).

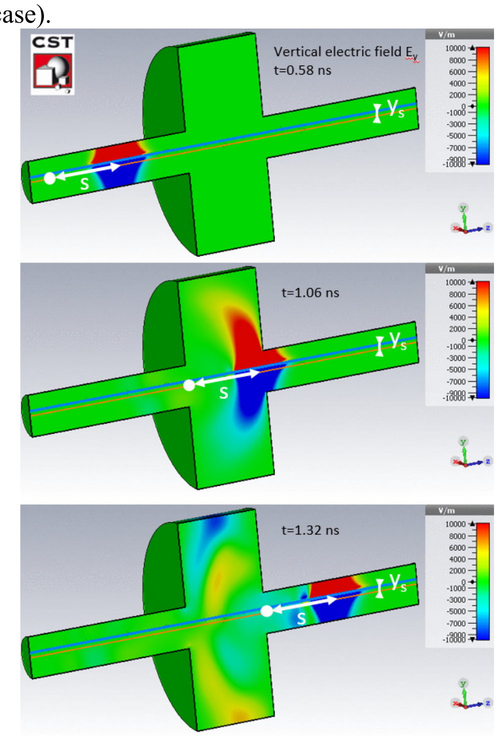

Figure 1: Snapshots at 3 successive times of the simulated vertical electric field with CST [4] of a source bunch travelling along the blue line, which is offset by y_s with respect to the centre of the cavity (orange line). The test charge (white dot) travels along the orange line at a distance s behind the source bunch.

Therefore the resulting horizontal wake function writes $W_x\,(s,x_s,x_t,y_s,y_t)$ as a function of the transverse coordinates of the source (x_s, y_s) and test charges (x_t, y_t), or $Z_x(f, x_s, x_t, y_s, y_t)$ in frequency domain, with similar dependences for vertical and longitudinal planes [5]. In principle, one should compute these impedances in all realistic combinations of source and test charges coordinates to estimate the impact on beam dynamics, but fortunately our current understanding of beam dynamics allows us to focus on a limited set of contributions.

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Which Impedance Contribution(s) Do We Need?

The impedance of interest indeed depends on the beam dynamics effect that is being studied: for longitudinal beam stability, one needs both real and imaginary parts of the longitudinal impedance $Z_{long}(f)$ as a function of frequency f and the dependence on transverse offsets is generally neglected for small amplitudes as it is a first order term of the Taylor expansion in transverse coordinates x_s, x_t, y_s, y_t [6]. On the other hand, our current transverse beam stability models require the first order terms linear in x_s, x_t, y_s, y_t, as the constant term does not contribute to beam stability and only causes a change of transverse closed orbit [5]. Higher order terms are usually not considered, except in [7]. The linear terms of the wake with respect to the source charge transverse offset x_s, y_s give the same transverse kicks to all test particles trailing at a given distance s behind the source charge and only depends on the source charge transverse offset: the kick is coherent and can drive coherent instabilities. These terms are called *driving wake* [8] or *dipolar wake*: the kick to the test particle is constant regardless of its offset, as in a dipole.

In contrast, the linear terms of the wake with respect to the test charge transverse offset x_t, y_t kick the test particles at a given distance s with an angle that is linear with their amplitude, as in a quadrupole. The resulting kick is incoherent, would generate betatron tune spread and these terms are called *detuning wake* [8] or *quadrupolar wake*. Thus, one needs real and imaginary parts of both transverse driving and detuning impedances $Z^{driv}(f)$ and $Z^{det}(f)$ for both planes: the impedance needed to estimate beam dynamics for one accelerator element is not a single number such as the effective impedances Z^{eff} or $Z_{long}{}^{eff}/n$ (i.e. the impedance convoluted with the bunch oscillation spectrum [1] with $n=f/f^{rev}$ and f^{rev} the revolution frequency), but 5 complex functions of frequency: $Z_{long}(f)$, $Z_x^{driv}(f)$, $Z_x^{det}(f)$, $Z_y^{driv}(f)$ and $Z_y^{det}(f)$, that may change along the machine cycle with energy, optics and moveable device position. Moreover, coupled impedance models $Z_{xy}(f)$ may be required to account for skew elements, for which horizontal kicks depend on vertical offsets [9]. A typical particle accelerator contains more than 100 such elements (RF cavities, magnets, instrumentation, septa) that can be assembled in an impedance model in order to perform global beam dynamics studies.

WHAT IS AN IMPEDANCE MODEL?

Any accelerator component directly seen by the EM fields of the beam generates wake fields, and these wake fields from all machine components add up to perturb beam dynamics. Provided the related beam dynamics effects, such as instabilities, do not develop too fast with respect to the machine circumference, all these kicks can be lumped into an impedance model [10] that folds all the impedances of all the elements of the machine into a single set of functions. Such impedance (or wake) models have been developed for many accelerators as they are key ingredients to evaluating their performance. The vertical driving impedance of the CERN LHC current impedance model during collisions is given in Fig. 2.

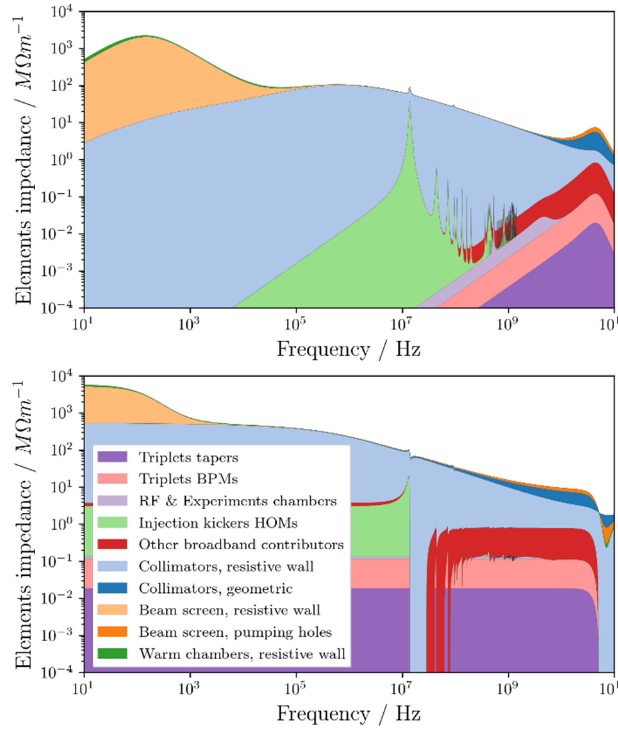

Figure 2: Cumulative plot of the vertical driving impedance (real on top and imaginary on bottom) as a function of frequency for the current impedance model of the CERN LHC in log-log axis with respective contributions [11].

WHY BUILD AN IMPEDANCE MODEL?

There are 3 main reasons to build the impedance model of a particle accelerator and keep it up-to-date.

To Predict Beam Instability Thresholds

When designing or upgrading a particle accelerator, the nominal design intensity and brightness should keep a suitable margin with respect to expected thresholds for beam stability. An accurate impedance model used as input of beam dynamics codes allows predicting the expected thresholds with respect to impedance-related instabilities, and also allows assessing whether the available mitigation techniques are sufficient to reach the design performance. Accurate impedance models can indeed verify before commissioning that new designs and ongoing upgrades will not limit the expected beam performance, as for the Future Circular Collider (FCC) beam screen aperture that needed to be increased to avoid transverse instabilities expected from the early impedance model [12]).

To Identify the Major Impedance Contributors

In case a brightness limitation is found around the expected limit, it is useful to have a quantitative overview of the relative impedance contributions of the elements in the machine in order to guide an impedance reduction campaign. In this respect, the example of the High Luminosity LHC (HL-LHC) upgrade is eloquent: its goal is a factor 2 increase in transverse bunch brightness compared to the current LHC, while the LHC itself already operates close

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to the limit of transverse stability [13]. Therefore an impedance reduction was needed. From Fig. 1 it is evident that the resistive-wall contribution of collimators (in light blue) is the major impedance contributor in the frequency range of interest (10 kHz-2 GHz) and that it should be the target of the impedance reduction. The upgrade of the bulk collimator material with low resistivity coating, planned to be installed in the next two long LHC shutdowns, is now expected to recover similar operational margins for HL-LHC operation as for the current LHC operation [13].

To Warn that Ingredients Are Missing

In case a brightness limitation is found well below the limit predicted by the impedance model, it is a clear sign that a major ingredient is missing in the understanding. It could be that the impedance of some elements was underestimated: this is for instance the hypothesis put forward to explain the three-fold difference between measurements and simulations in both longitudinal and transverse planes for MAX IV [14]. Prediction of stability thresholds can also miss ingredients that do not depend on the impedance. There an accurate impedance model helps disentangling the sources of issues: large discrepancies in measured stability threshold in the LHC - while tune shifts from the impedance model agreed reasonably well with observations - allowed identifying the destabilizing effect of beam-beam long range [15], linear coupling [16], transverse damper [17] and noise [18].

HOW TO USE AN IMPEDANCE MODEL?

Before building the impedance model of a machine, it is important to define its use-cases in order to tailor appropriately its parameters. By itself, the impedance model allows comparing the impedance of proposed changes to the full model. This enables an *Impedance police* to quickly grasp the extent of the change. Nevertheless, that quick approach needs to be supported by an assessment of the impact of impedance on beam dynamics. There are two main families of tools to compute beam dynamics related effects linked to impedance: Vlasov solvers and macroparticle simulations. A comprehensive overview of such codes is given in [19]. Using the impedance as a perturbation of the beam mode eigensystem, frequency domain Vlasov solvers compute coherent tune shifts and rise times of instabilities from the impedance in frequency domain. Macroparticle tracking codes may expect wake functions as inputs in order to give kicks at every turn to trailing macroparticles. Single bunch simulations require short range wake functions, while coupled bunch multi-turn simulations require long range wake functions. Several tools require fitting the impedance by one or more resonators but more recent tools can now take any impedance or wake as inputs (with correct range and sampling). Since the number of points of the computed wakes is a limitation, the required frequency range and sampling for the beam dynamics code(s) is a crucial information before starting the simulation and assembly of the impedance model. For instance, not only the short range wake function model used to benchmark single bunch SPS instabilities with macroparticle simulations could not be used for coupled bunch stability studies (as it was missing the long range contribution), but it could not even be used for single bunch frequency domain Vlasov solvers as the frequency sampling after Fourier Transform was inadequate. When possible from the beam physics point of view, it is advised to split the studies into single bunch and multi-bunch since computing the impedance over a very large frequency range can be very challenging.

Besides the frequency range and sampling, the relativistic gamma factor for the machine should be known in advance as it has a significant impact on the impedance itself, and on the way it can be obtained (since many impedance codes and formulae make the assumption of an ultra-relativistic beam).

HOW TO BUILD AN IMPEDANCE MODEL?

One needs to identify the elements to be addressed, compute their impedance contribution, assemble them consistently in an impedance model, compute expected beam observables from this model and compare them with measured beam observables. It should be noted that high frequency fields excited by the beam beyond the beam pipe cut-off travel around the machine and are not accounted for in the model, as the lumped impedance assumption is used.

Identifying the Main Impedance Contributors

With infinite time and resources, one would compute the impedance of all machine elements. Since accelerators can be very large facilities, experts usually start with the usual impedance suspects: those with large individual impedance – geometric (RF cavities, stripline kickers, insertions) or resistive-wall (ferrite kickers, ceramic chambers, low conductivity collimators) and those in large numbers (instrumentation, vacuum chamber, vacuum flanges, vacuum valves, bellows). Some large impedance contributors are sometimes much more difficult to identify due to non-conformities between design and installation, inadequate connection, misalignments, unknown material parameters (in particular for non-metallic components and thin coatings). Such hidden impedance contributors are particularly difficult to identify in old machines, with ageing equipment for which experience and documentation could get lost, and successive interventions are more difficult to trace.

Computing the Impedance of Single Elements

There are nowadays many tools at our disposal to compute the impedance of single elements: theoretical formulae and codes, time-domain and frequency domain simulation codes, RF measurements on a bench, and even measurements with particle beams.

Explicit theoretical formulae were derived for ideal simple geometries: e.g. perfectly conducting wall (also called indirect space charge impedance, ISC), resistive wall (RW) in the thick wall approximation, stripline beam position monitors (BPMs), pill-box cavities, resonator model, iris, pipe transition, window-frame and travelling wave kickers, holes and slots in beam pipe, obstacle, roughness, taper, coherent synchrotron radiation (CSR) [20] and references

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therein. Codes using field matching (IW2D [9]) and transmission line [21] formalism can compute the resistive wall impedance for infinitely long multi-layered cylindrical beam pipe and flat chamber geometry. Codes using mode matching compute the impedance of finite length devices [22]. Whenever possible, the use of such analytical estimations is preferred as there is no numerical noise and much less stringent computing limitations on the final frequency range compared to 3D simulation codes.

Nevertheless for more complicated geometries, one needs to resort to heavy 3D simulation codes, which allow drawing or importing 3D models of arbitrary size and complexity and discretizing the geometry into small mesh cells in which Maxwell's equations can be solved in time or frequency domain with a source excitation. Each of these codes has its advantages and drawbacks: from license costs and various usage restrictions (e.g. geographical, operating system, cluster, type of organization) to the technical capabilities of the code (possibility to simulate in frequency domain, time domain, with a bunch as excitation source, to parallelize simulations on cluster, to use tetrahedral or hexahedral mesh cells, to allow the use of materials with arbitrary frequency dependent properties, to allow for different integration methods). All these arguments enter in the choice of an adequate tool.

Wakefield simulation is the most direct way to compute impedance since the excitation source is a simulated particle bunch. However, the need to define a finite source bunch length enhances numerical noise and limits the higher limit of the frequency range due to the need to divide by the source bunch spectrum to obtain the impedance. The solution would be to use an extremely small bunch length, but the requirement to keep a reasonable ratio between the bunch length and the mesh size prevents using very short bunches. The efficiency of simulation tools has improved a lot for the past two decades (thanks to code optimization, parallelization and increased computer power), but computing time and power is still a major limitation to simulating some geometries, in particular with lepton-scale bunch lengths. In that case, the moving mesh approach available in some of the codes is advantageous to compute short range wakes [23].

Eigenmode solver finds the modes that resonate inside the simulation domain and is a powerful complementary tool to the wakefield solver. However, its task is much more difficult with frequency dependent materials, which require meshing inside them and it is currently restricted to resonant modes below cut-off of the outgoing vacuum chamber, even though there is some hope that this can be implemented in the future [24]. Another drawback is the need to compute the impedance mode by mode, which can be very inefficient when the bunch can excite a lot of modes inside the structure. Recently, new frequency domain simulation techniques were reported: work towards a frequency domain impedance solver was successfully implemented for 2D structures, but not yet extended to 3D [25], and a travelling wave method allows computing the impedance of periodic structures such as beam screen holes and slots with high accuracy [26]. Table 1 summarizes whether impedance contributions can be obtained directly or indirectly from common theoretical, simulation, RF measurement and beam-based tools, accounting for the possibility to disentangle driving and detuning impedances from eigenmode simulations that is recently reported in [27]. It also shows whether the ultrarelativistic β=1 approximation has to be used for that technique.

Table 1: Access to Impedance by Available Techniques

Common tools (theory, simulation, RF measurements, beam-based)	β=1?	Access to longitudinal impedance	Access to transverse impedance	
			driving	detuning
IW2D [18]	β≤1	direct	direct	direct
Wakefield	β≤1	direct	direct	direct
Eigenmode	β≤1	indirect	indirect	indirect
1-wire meas.	β=1	indirect	indirect: $Z^{driv}(f)+Z^{det}(f)$	
2-wire meas.	β=1	N/A	indirect	no
Probe meas.	N/A	no	no	no
Tune shift	β≤1	$Im(Z^{eff}/n)$	Only $Im(Z^{driv\ eff}+Z^{det\ eff})$	
Instab. growth rate	β≤1	$Re(Z^{eff}/n)$	$Re(Z^{driv\ eff})$	no

In spite of significant improvements of these tools over the years, the critical challenge for impedance computation remains to perform the correct simplifications on the geometry and to make the correct assumptions on material properties. This is why it is crucial to benchmark the computations among themselves (e.g. eigenmode and wakefield simulations to check for mesh-related issues), but also with measurements on the real device. Measurements on an RF bench allow access to the impedance observables through excitation and pickup of RF signals with either a stretched wire, probes or a bead. As seen in Table 1, the longitudinal impedance can be estimated from the measured scattering parameters with a wire using the appropriate formula [28], while the transverse impedance can be obtained by using a combination of displaced single wire measurements (that yield the sum of driving and detuning terms) and a two-wire measurement that yield the driving term [29]. It has to be noted that these measurements are not trivial to set up [30] and that the large perturbation to EM fields introduced by the wire calls for benchmarking the measurement results with simulations of the RF measurement set-up including the wires. This latter comment applies to probe measurements that are used to confirm the presence of harmful resonant modes. Last, material EM properties should be measured if their frequency dependence is not known (e.g. ferrite, dielectric, and coating).

Once installed, validation beam measurements can take place by orbit bump, local phase shift with intensity or if the device is moveable. Synchronous phase shift and betatron tune shift measurements give access to the differential effective longitudinal and transverse - $Im(Z^{driv\ eff}+Z^{det\ eff})$ - impedances between two positions of the moveable device. Lately, the precision of measurements with the transverse damper significantly improved, in the LHC for instance, and could reach of the order of 10^{-5} for tune shifts [31].

Assembling Impedances in a Consistent Model

The longitudinal impedance model is a simple sum of the longitudinal impedance contributions, while the transverse

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impedances need to be weighted by the ratio of the β-function at the device location to the reference β-function used by the beam dynamics tool [10]. The main difficulty for the impedance model assembly lies in harmonizing contributions that may originate from different codes: theoretical codes for resistive wall impedance (vacuum chamber and collimators) and simple geometries (e.g. bellows); simulation codes for more complex geometries (e.g. kickers, instrumentation, transitions and RF cavities). Their sampling, level of noise, and source bunch length for wakefield simulations can be very different. It is sometimes better to leave out some low impedance contributors as their noise may pollute the entire model. A tricky question is also whether it is advantageous to use directly the wake potential from the wakefield solver instead of performing the deconvolution by the source bunch spectrum that may yield a much noisier wake function.

Impedance models exist for almost all lepton and hadron machines, as seen in Table 2, but differ in level of complexity depending on needs and available resources: some models include only one contributor (e.g. indirect space charge for SIS-18), others use fitted broadband resonator (BBR, as many light sources), while some need to account for many frequency-dependent contributions (*f* dep. in Tab. 2).

Table 2: Measured machine impedances Im(Z_{long}^{eff}/n) and Im(Z_y^{eff})=Im($Z_y^{driv,\ eff}+Z_y^{det,\ eff}$), with percentage missing in the model to reproduce the measured impedance with beam.

Lepton/hadron machine	Im(Z_{long}^{eff}/n) [Ω] meas.	missing	Im(Z_y^{eff}) kΩ/m meas.	missing	Ref. and model contributors
ALS	0.42	40%	110	-36%	[32] BBR
AS	0.36	-17%	130	-15%	[32] BBR
ELETTRA	0.42	-43%	230	35%	[32] BBR
ALBA	0.39	-8%	310	71%	[32] BBRs
SOLEIL	0.54	61%	620	68%	[32] BBRs
TPS	0.51	27%	440	100%	[32] BBR
MAX IV	0.51	82%	470	81%	[32] BBRs
Diamond	0.46	57%	334	25%	[32],[33] BBR
NSLS-II	0.5	66%	650	40%	[32] BBR
ESRF	0.7	29%	566	50%	[34] BBRs
APS	0.57	26%	680	26%	[32] *f* dep.
SPRING-8	0.24	46%	220	5%	[32] *f* dep.
PEP-II	0.17	41%	80	-6%	[32] *f* dep.
PETRA-III	0.37	51%	620	37%	[32] BBR
KEKB	0.14	93%	50	70%	[32] BBRs
PSB injection	796	24%	12000	9%	[35] *f* dep.
PSB top			2500	20%	[35] *f* dep.
LEIR	40000	20%	552500	20%	[36] *f* dep.
PS top	18.4	-5%	2230	1%	[37] *f* dep.
SPS	1.25	20%	17500	7%	[38],[22] *f* dep.
LHC	0.09	0%	37800	30%	[39],[11] *f* dep.
FNAL RR			12000	-75%	[40] *f* dep.
RHIC blue	1.5	33%	3200		[41],[42] *f* dep.
RHIC yellow	5.4	81%	14000		[41],[42] *f* dep.
JPARC MR			7000	-50%	[43] ISC+RW
SIS-18			385762	13%	[44] ISC

Comparing Model to Measured Beam Observables

Now that the model is assembled, it should be benchmarked against available beam-based observables in order to gain confidence in the stability thresholds that can be predicted with that model. Typical beam-based observables that can be simulated and used to benchmark the impedance model to the real machine include bunch lengthening, instability thresholds and growth rates (loss of Landau damping, mode coupling, microwave), coherent and incoherent frequency shifts with intensity [32, 45]. Here it is important to recall that most beam-based observables result from the convolution of the impedance with one or several modes of oscillation, and scans in relevant parameters are needed to check that both the simulated value and its frequency dependence matches measurements, as in the successful SPS benchmarks for bunch length dependence on quadrupole frequency shift [38], and chromaticity dependence on transverse instability growth rates [21]. Besides, one can see from Table 2 that impedance models are typically within a factor 2 margin with respect to measurements. Lepton machines have consistent effective impedances (0.1 to 0.6 Ω and 100 to 650 kΩ/m), while hadron machines present a large spread, due to less optimized impedance designs (with the exception of LHC), but also to the impact of indirect space charge at low beta.

MAIN CHALLENGES AHEAD

Computing power has recently allowed very long simulations with unprecedented number of mesh cells, but critical challenges remain to build an accurate impedance model with reasonable resources: truncate optimally the list of impedance contributors; make the correct assumptions for material properties and geometries over the frequency range of interest; perform benchmarks with several impedance codes with convergence studies; find a flexible way to recompute the model for changes of gaps, energy, β-functions, bunch length; and finally optimise the beam-based measurement procedures and instrumentation.

Major difficulties with impedance simulations lie in fighting numerical noise for small impedances present in large numbers, simulating coatings and roughness in 3D codes, addressing 2-beam impedance, assessing high frequency material properties and accounting for external connections: the recent experience in two separate accelerators of instabilities caused solely by the inadequate termination of one single machine element [46] shows the level of detail needed to build an accurate impedance model. Indeed, low impedance is only one of the many ingredients to reach beam stability in particle accelerators, and it is important to minimize the impedance uncertainties so that they do not blur the picture for the other fields of research.

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