Characterization of the dielectric strength in vacuum of RF drivers for Neutral Beam Injectors Ion Sources

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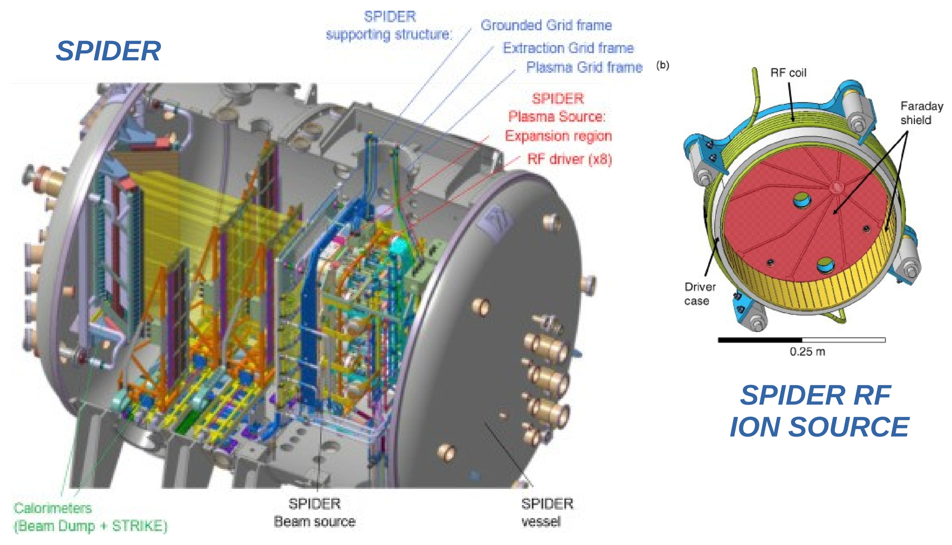
PRIMA: THE ITER NEUTRAL BEAM INJECTOR TEST FACILITY

PRIMA (**P**adova **R**esearch on **I**njector **M**egavolt **A**ccelerated) is the Neutral Beam Test Facility for ITER being built in Padova (Italy), where two main experiments will take place:

- SPIDER (**S**ource for **P**roduction of **I**on of **D**euterium **E**xtracted from **R**f plasma) is the full scale prototype of the RF Ion Source used for heating and diagnostic beams;
- MITICA (**M**egavolt **IT**er **I**njector & **C**oncept **A**dvancement) is the full scale prototype of the heating beam, with the acceleration up to 1 MV.

The ions are produced with 8 Radio Frequency (RF) drivers, supplied by 4 independent and identical circuits composed of:

- RF generator rated for 200 kW working at 1 MHz;
- Coaxial cables with 50 Ω characteristic impedance;
- Matching network for load adaptation;
- 2 RF coils connected in series.



1. PhD topic and motivation

For ITER Neutral Beams Radio Frequency driven ion sources have been selected for their advantages, in particular in terms of reduced maintenance.

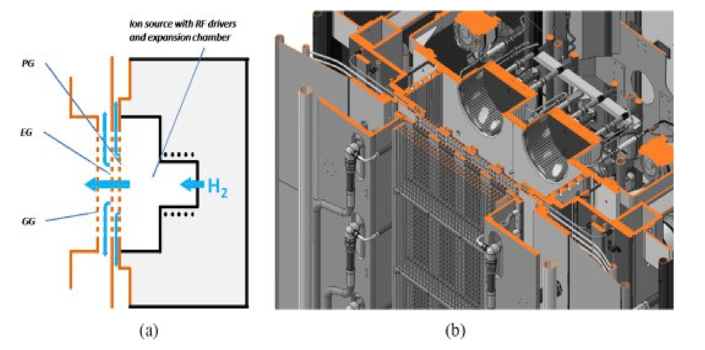
One of the issues encountered in this type of ion sources, and associated to radio frequency, is the **occurrence of breakdowns on the RF coils.**

Lack of experimental history within the NB community on the **RF voltage holding in vacuum** pushed on the experimental investigation proposed with this PhD thesis.

2. Scope of the work

The scope of the work is to reproduce the conditions of the RF coils used in the ion source for ITER in terms of voltage and pressure:

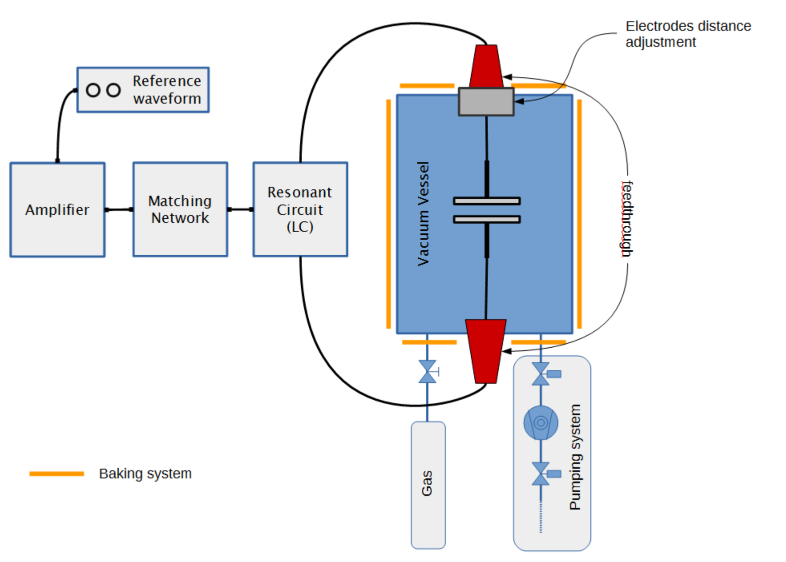
- The voltage across the RF coil reaches **15 kV rms, 1 MHz;**
- The operating pressure is in the range of pressure of **0.001 - 0.3 Pa.**



Sartori et al.
doi:10.1016/j.vacuum.2015.05.028

3. Test facility idea

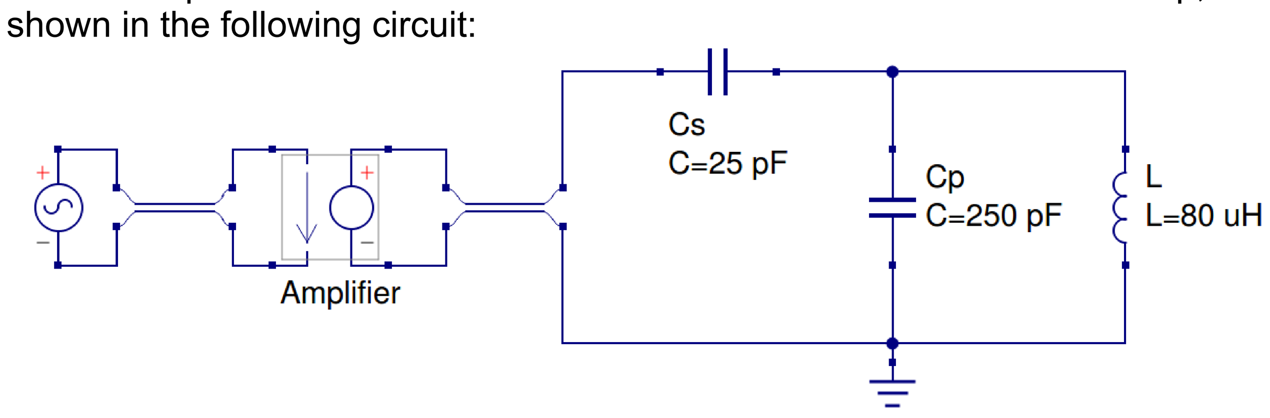
The idea is to produce the High Voltage with a radio frequency inductive-capacitive resonant circuit, connected to a low voltage power amplifier.
The voltage will be applied to a couple of electrodes of different shapes placed inside a vacuum vessel capable of producing a pressure range of 10^5 Pa - 10^{-3} Pa.
To optimize the power transfer (minimize the reflected power) the load seen from the amplifier has to present an impedance of 50 Ω; if the LC resonant circuit differs from such value (which is the case) there is the need of a matching network.
The system working principle is sketched in figure below:



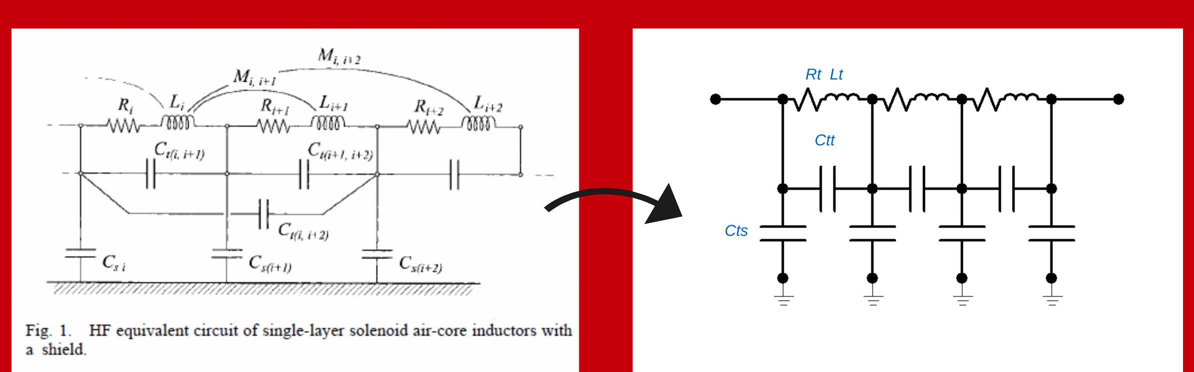
One of the main aims of the resonant circuit design is to improve the efficiency as much as possible, such to **achieve the target voltage with the minimum losses. The characterization of the circuit components** by means of **measures and suitable models**, capable to reproduce their behaviour around the working frequency, is necessary at this purpose.

3. Resonant circuit and matching network

A first resonant circuit and matching network was realized using commercial vacuum capacitors and an inductor realized at Consorzio RFX workshop, as shown in the following circuit:



During some preliminary tests the resistance of the inductor was found to be almost double than expected. The power losses are caused by the stray parameters of the components of the circuit, mainly the resistance of the inductor (since vacuum capacitor are used). It was found that **the stray capacitances** (turn to turn and turn to ground or shield) **have an impact on the resulting resistance and inductance of the inductor → different resonant frequency and higher power losses!**

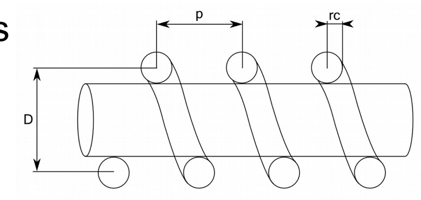


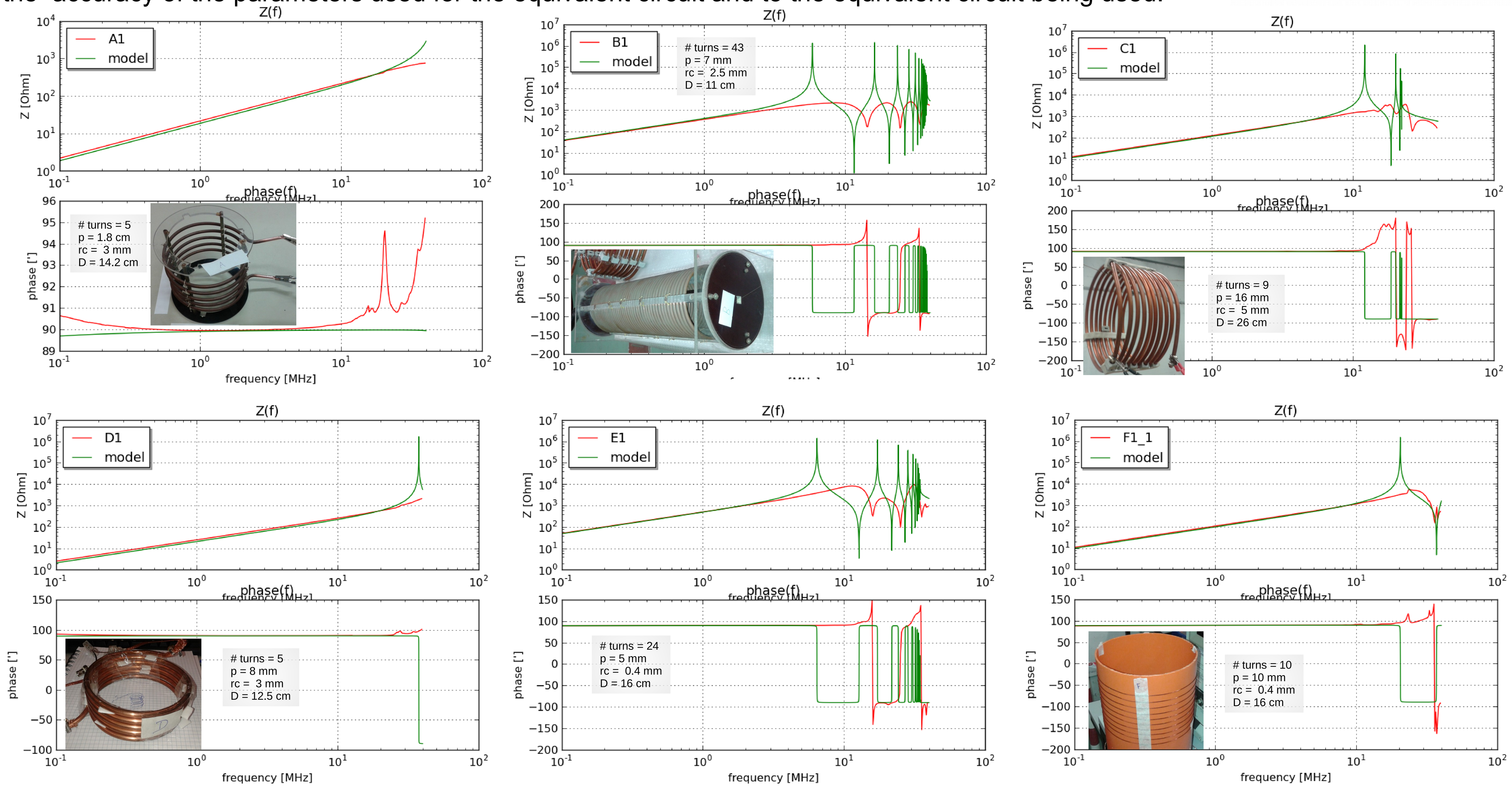
On literature it was found that **single layer solenoid** has the lowest stray capacitances and therefore lower power losses.

The strategy has been to **develop reliable models to predict the effective resistance and inductance of the inductor** and to validate them against measurements on coils of different size.

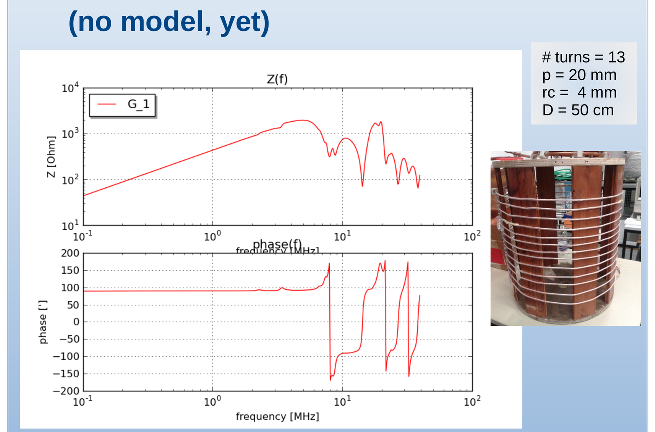
4. Validation of the electrical model of the inductor against measurements

The electrical model of the inductor is built starting from the geometry of the inductor, the material properties and the range of frequency in which it will be used. A Python program calculates the resistance, inductance and the stray capacitances of each turn, then the impedance is derived accounting for the complete equivalent electric circuit. The capability to reproduce the operation at high frequency is strongly related to the accuracy of the parameters used for the equivalent circuit and to the equivalent circuit being used.



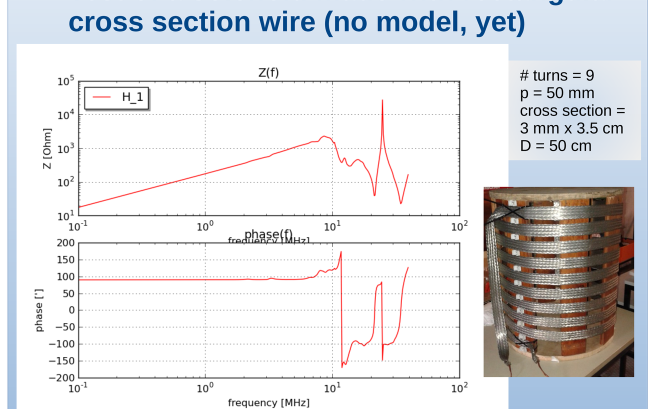


Test of a solenoid made with Litz wire (no model, yet)



The resistance offered by the inductor at 1 MHz is 1.96 Ω, too high!

Test of a solenoid made with rectangular cross section wire (no model, yet)



The resistance offered by the inductor at 1.7 MHz is 730 mΩ, not bad but the material is not being used as it could → current distributes only on top and bottom of the wire.

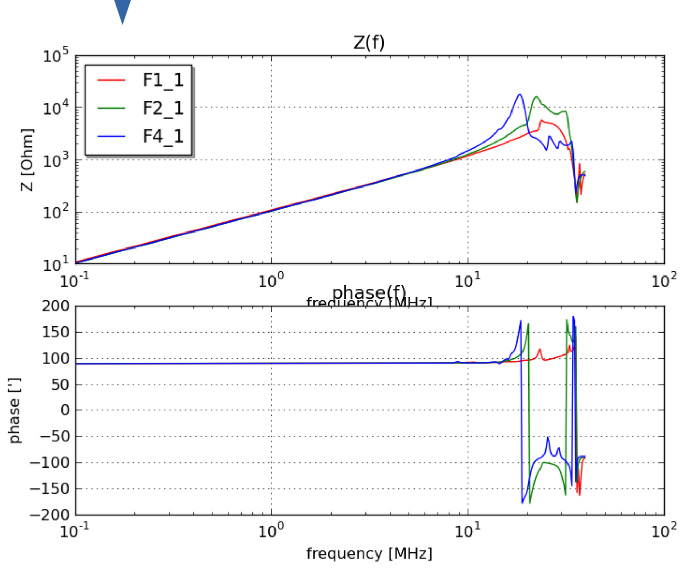
The model overestimates the stray capacitances, and need further improvements. Nevertheless the prediction of the impedance around 1 MHz is satisfactory.

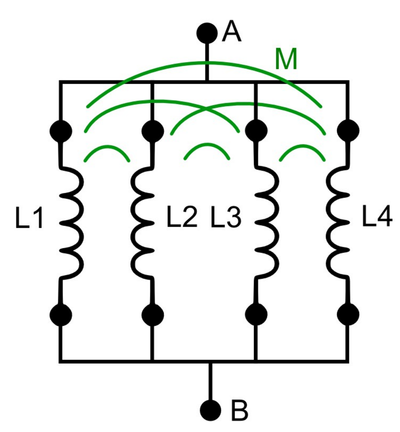
The model predicts multiple self resonance frequencies which are found experimentally! Other models which concentrates the stray parameters show only the first resonance.

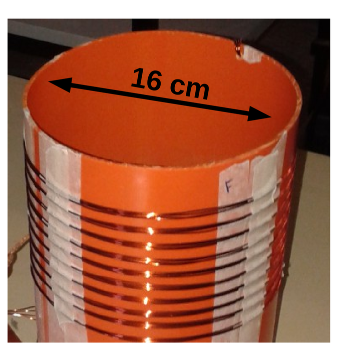
5. Tests on coupled inductors paralleled

Winding many inductors mutually coupled and electrically paralleled would **decrease the overall resistance without changing the value of the inductance** seen from the circuit: the difficulty is to have a good current sharing!
First tests on a 4 small inductor mutually coupled gave **good results**.

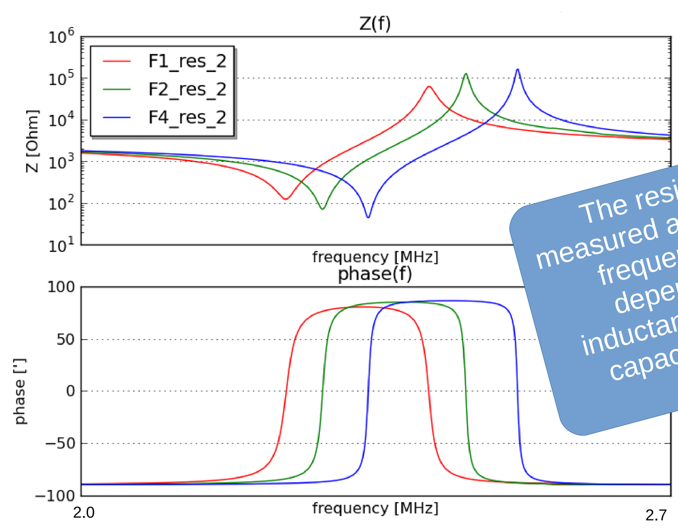
F1 is the inductor with only one wire.
F2 is the inductor made winding two insulated wires.
F4 is the inductor made winding four insulated wires.



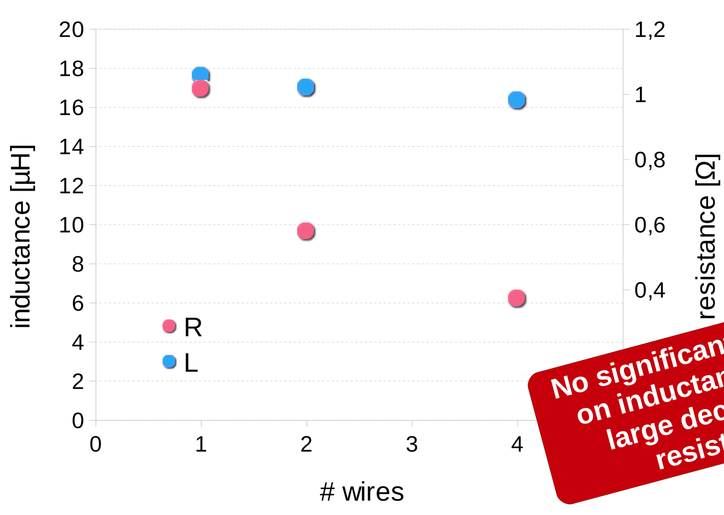




To measure the resistance the resonant circuit is used!



The resistance is measured at the resonant frequency, which depends on the inductance and on the capacitors used for measure



No significant variation on inductance, while large decrease of resistance!

6. Conclusions and future works

The work performed on the models development and validation via a wide measurement campaign on different inductors (in terms of size, number of turns, pitch, …) allowed and advancement on the comprehension of the role played by the stray parameters on the inductor behaviour. This gives precious indications for the design of components (such as RF coils for ions sources) with an improved efficiency.
In the near future a coupled inductor of the required inductance will be built and tested with RF power. During the tests on the inductor, the need of a shield for EM field will be verified, as well as possible provision (see P. Jain poster).

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