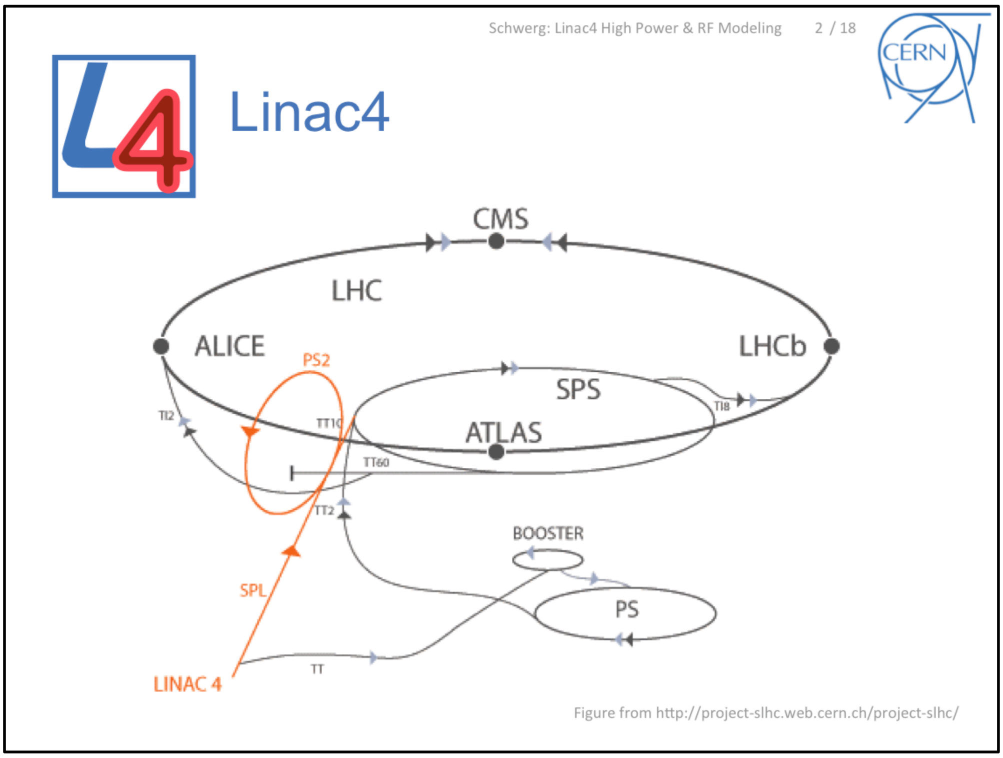
Nikolai Schwerg – CERN / BE / RF / KS - nikolai.schwerg@cern.ch

Linac4 High Power Distribution Analytical RF Network Modeling

RF TECH – PSI Villingen

03 December 2010

The slides contain as little text as necessary. A transcript and additional information are in the notes printed below.



Part of the SLHC upgrade plan – see CERN accelerator complex with planned/studied upgrades in orange

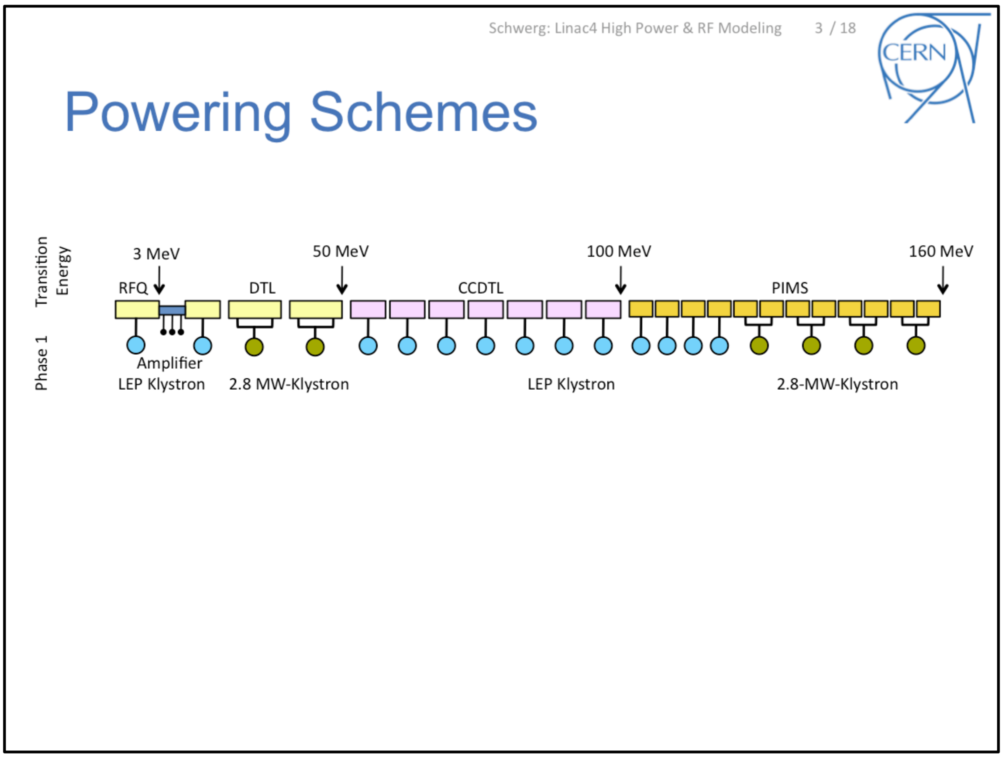
Accelerates (H-)-ions to 160 MeV with a rep rate of 2 Hz

Will replace the Linac2, the first element of the accelerator chain. Connection to the PS Booster in 2016.

Can be extended to the SPL

Some facts:

- av. Power 10kW
- Peak Power 2.8 MW or 1.3 MW
- Rep Rate 2 Hz
- Pulse length 1.6 ms



The accelerator consists of RFQ, DTL, CCDTL and PIMS operating at 352.2 MHz.

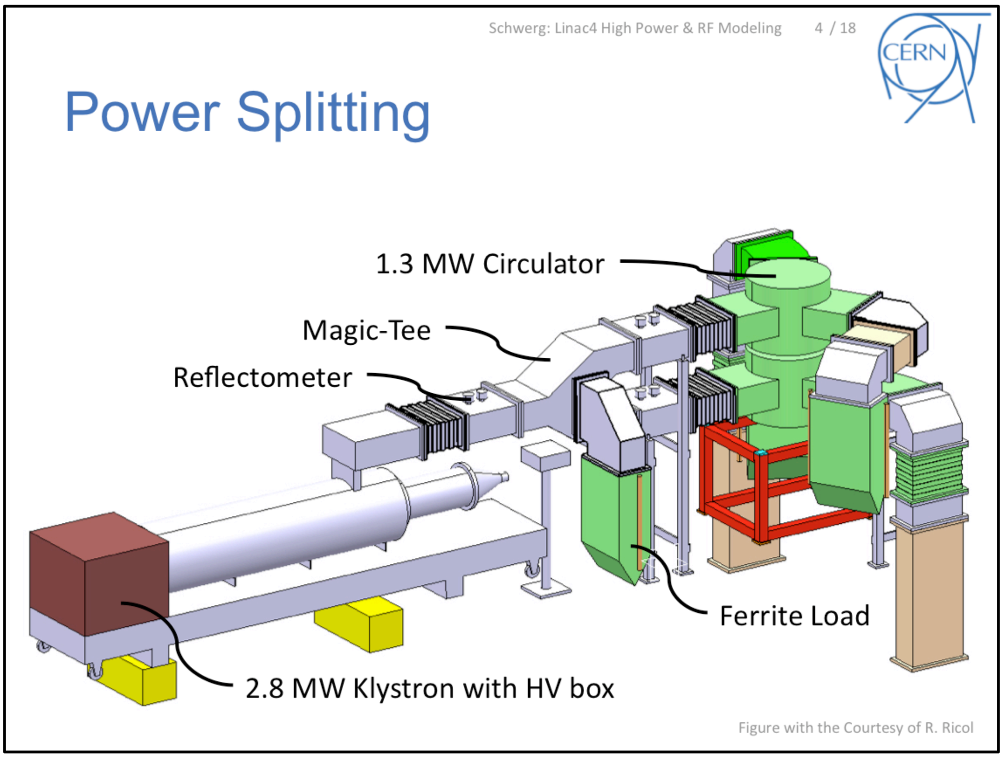
The design of the RF powering scheme was based on the following 3 objectives:
- maximum reuse of LEP equipment,
- limited space for the installation at high beam energy (+/- 5%, +/- 0.5 deg)
- Phase and amplitude constrains, especially for the DTLs

Available LEP equipment are:
- 1.3 MW Klystrons
- 1.3 MW Circulators
- Waveguides

The powering scheme is split in 2 Phases:
- In Phase 1 we use as many of the existing klystrons, except where we can not due to space (PIMS end) or phase (double DTLs). There we use new 2.8 MW klystrons.
- In Phase 2 pairs of LEP klystrons are replaced by new 2.8 MW klystrons.

This requires to split the power …

Abbreviations:
Radiofrequency Quadrupole
Drift Tube Linac
Cell-Coupled Drift Tube Linac
Pi-Mode Structure

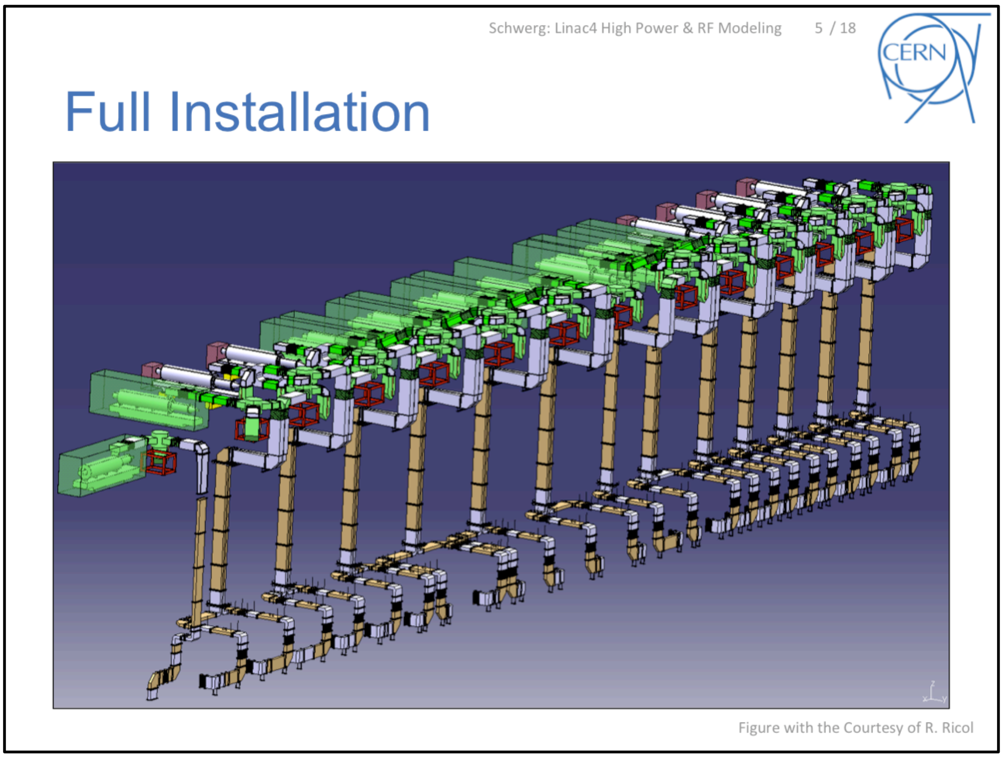


For the new 2.8 MW klystrons we are using the following power splitting scheme:

- The power from the klystron is distributed to two LEP circulators by means of a "folded magic-tee" and then connected down to the tunnel
- The circulators and the magic-tee are closed by a ferrite load (similar to the ones for LHC)
- For the LLRF, control of the power splitting and optimization of the circulator working point (current, temperature) we place reflectometers (bi-directional waveguide directional couplers) in each branch.

Splitting the power before the circulator can be seen as uncommon. It was decided to do so since (up to today) no 2.8 MW circulator for 352.2 MHz is available without the use of SF6-gas.

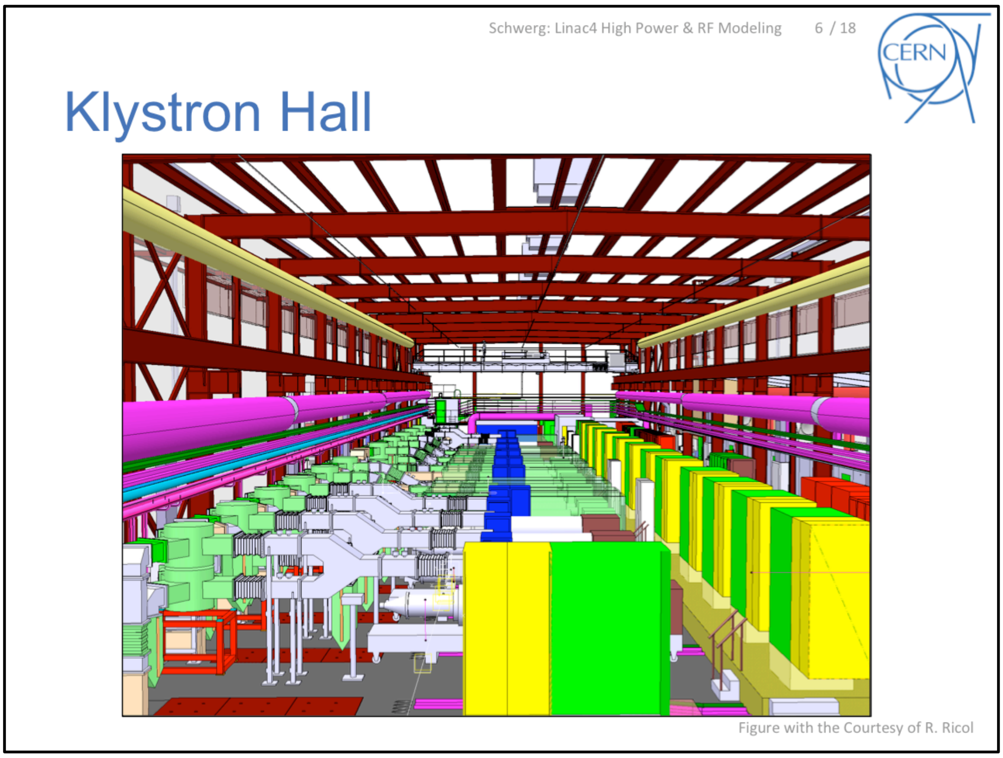
Due to the power splitting the phase of the two branches is coupled. Efforts are taken to reduce geometrical phase errors and provide compensation by means of 3-post phase shifters.



This image show the full waveguide system from the tunnel (without the accelerating structures) up to the klystron hall in Phase 1.

The LEP klystron are easy to distinguish due to the (green) lead garages.

At the moment we are waiting for the final drawings to estimate the phase errors and foresee compensation.



The Linac4 Building was inaugurated in October 2 weeks ahead schedule!

This shall show what will happen over the course of the next 4 years…

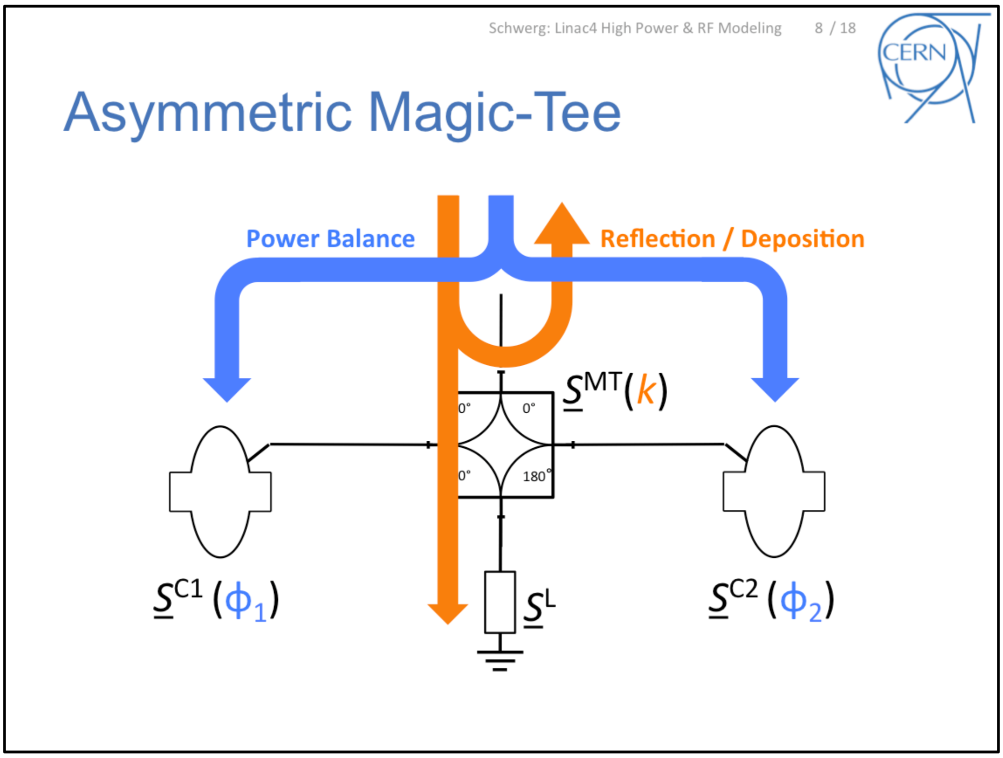
The design was presented at Linac10:

[BSC10] Olivier Brunner, Nikolai Schwerg, and Edmond Ciapala. RF power generation in Linac4. In
Proceedings of Linac10, October 2010.

Ongoing Studies

- Amplitude and Phase Errors
  - Installation
  - Phase-Shifter
  - Reflective Post
- Trapping of Higher Order Modes
- Circulator Control
- Validation of the Concept:

  Test Stand ready in Spring 2011



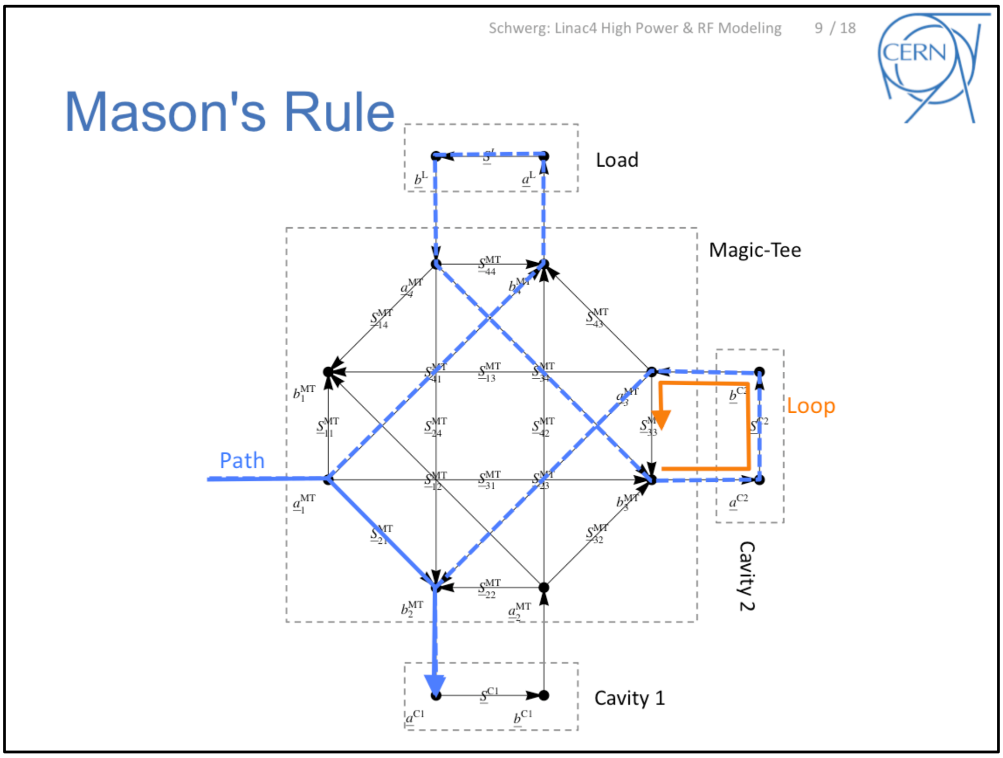
Before we can actually measure something we try to study aspects of the installation theoretically…

Simulations with standard tools such as HFSS and MWS have the following restrictions:
- Phase errors for extensive structures (FDTD)
- Computational effort
- Availability of numerical models

S-Parameter formulation allows to
- use ideal and measured values,
- Simplify waveguides by line theory
- Reduce the complexity

Interconnected device and their S-parameters can be described by signal flow graphs and be calculated with MASON's rule. I will illustrate MASON's rule by a reduced/ academic example and introduce a program for it's symbolical solution.

Let's have look at the following problem: The power from a source is split by means of a magic-tee to two cavities (see above). We investigate how the power distribution depends on the assymmetry of the magic-tee and the phase of the cavity reflection, 1.



In the signal flow graph every wave quantity is represented by a node and every connection (S-parameters) by an arrow.

The figure shows the flow graph of a magic-tee with the highlighted path from port 1 to port 2.

After we connect the two cavities and the loads, new connections from port 1 to 2 emerge. Therefore, the transfer function for an inter connected system consists of the contributions of all possible paths between the two nodes. Hans-Walter Glock calls this coupled s-parameters.

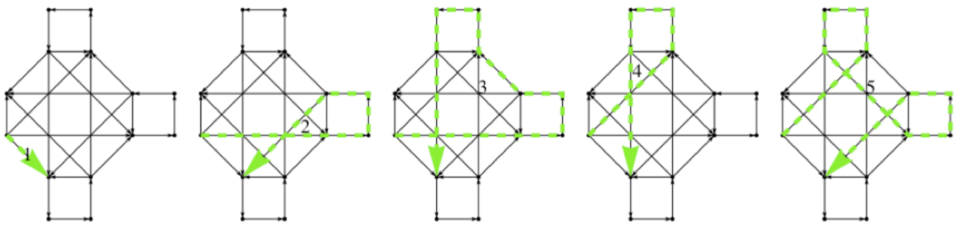
Furthermore, the interconnection introduced loops or resonators within the system, e.g here.

In the following we revise the MASON's rule and show an automatic means of evaluation.

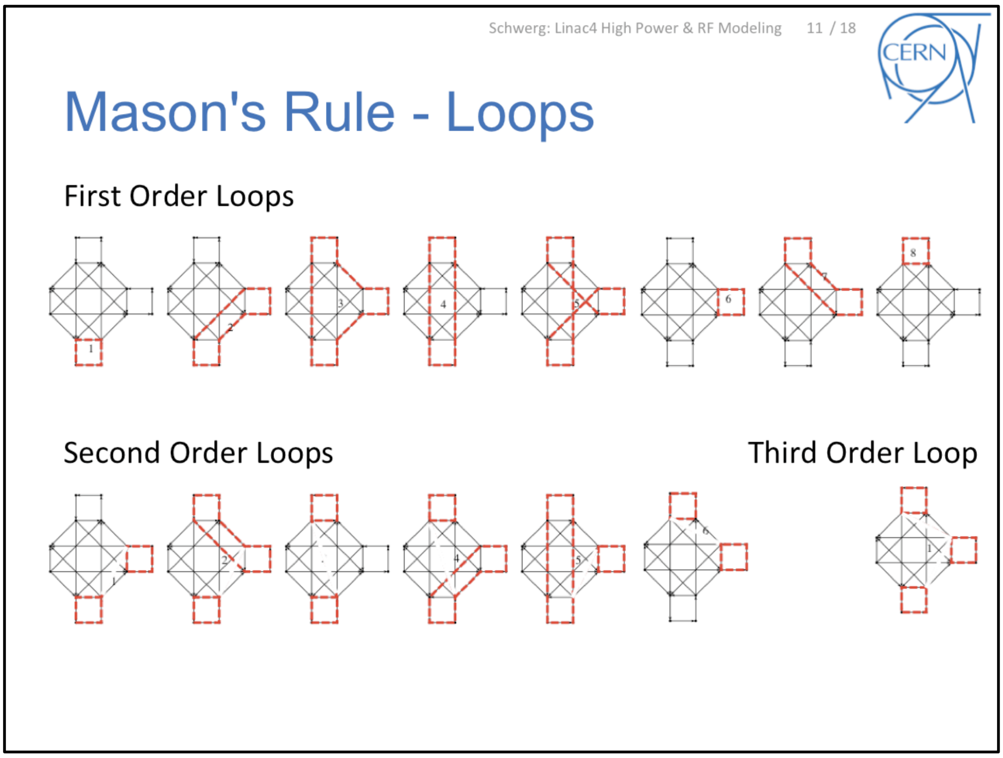
Compare:

[GRvR02] Hans-Walter Glock, Karsten Rothemund, and Ursula van Rienen. CSC - a procedure for coupled
S-Parameter calculations. IEEE Transactions on Magnetics, 38(2):1173–1176, March 2002.

Mason's Rule - Paths



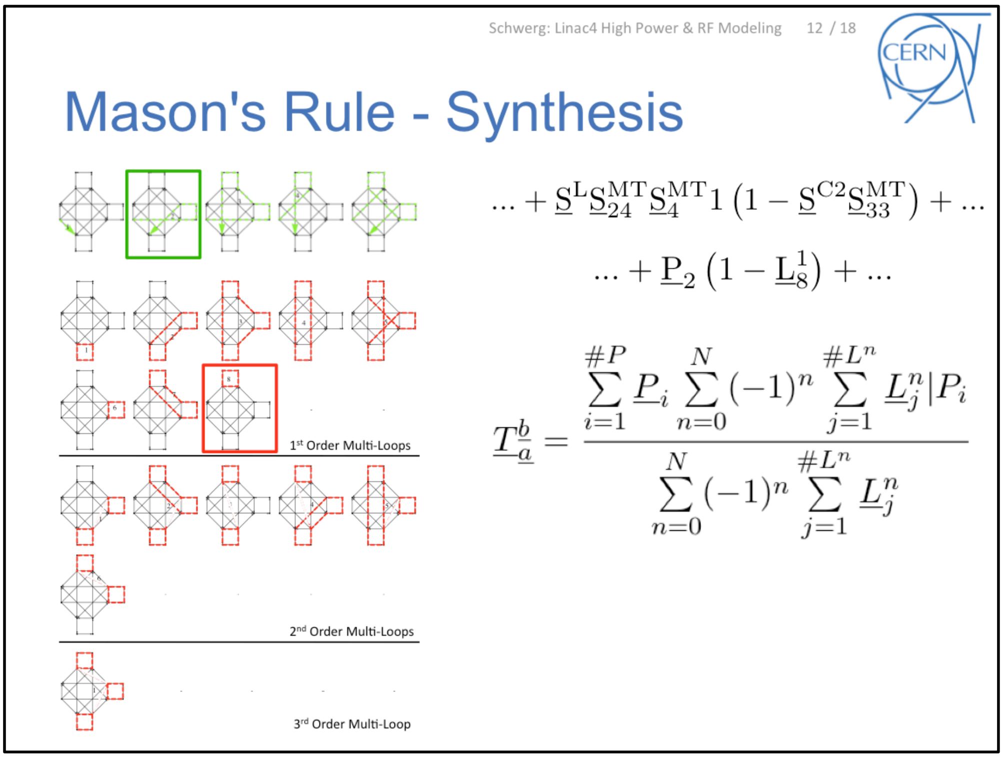
In addition to the direct connection we see 4 more paths from port 1 to port 2.



We can distinguish 8 different loops in the network.

Any set of two loops which do not share a node or a branch are called loop of second order – multi loop of order two.

We find 5 multi loops of order 2 and 1 of order 3.



The transfer function consist of every path between the two nodes weighted by their non-touching multi-loops with alternating sign, divided by all multi-loops of the network.

For the highlighted path the only non-touching loop is no. 8. This part of the expression we see here.

Full Analytical Expression

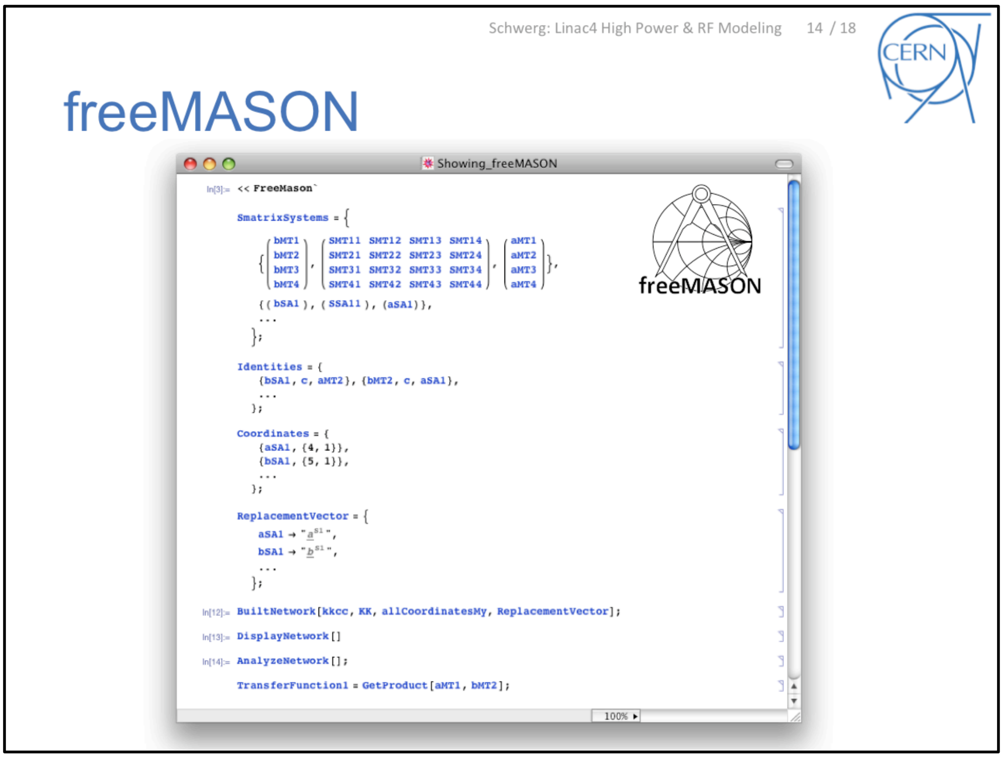
$$\underline{T}_{\underline{a}_1}^{\underline{b}_2} = \frac{\underline{b}_2}{\underline{a}_1} = \frac{\underline{S}_{21}^{MT}\left[\begin{array}{l} +1 \\ -\underline{S}^{C2}\underline{S}^{L}\underline{S}_{34}^{MT}\underline{S}_{43}^{MT} \\ -\underline{S}^{C2}\underline{S}_{33}^{MT} \\ -\underline{S}^{L}\underline{S}_{44}^{MT} \\ +\underline{S}^{C2}\underline{S}^{L}\underline{S}_{33}^{MT}\underline{S}_{44}^{MT} \end{array}\right] + \underline{S}^{L}\underline{S}_{24}^{MT}\underline{S}_{41}^{MT}\left[\begin{array}{l} +1 \\ -\underline{S}^{C2}\underline{S}_{33}^{MT} \end{array}\right] + \underline{S}^{C2}\underline{S}^{L}\underline{S}_{24}^{MT}\underline{S}_{31}^{MT}\underline{S}_{43}^{MT} + \underline{S}^{C2}\underline{S}_{23}^{MT}\underline{S}_{31}^{MT}\left[\begin{array}{l} +1 \\ -\underline{S}^{L}\underline{S}_{44}^{MT} \end{array}\right] + \underline{S}^{C2}\underline{S}^{L}\underline{S}_{23}^{MT}\underline{S}_{34}^{MT}\underline{S}_{41}^{MT}}{1 - \left[\begin{array}{l} +\underline{S}^{C1}\underline{S}^{C2}\underline{S}^{L}\underline{S}_{23}^{MT}\underline{S}_{34}^{MT}\underline{S}_{42}^{MT} \\ +\underline{S}^{C1}\underline{S}^{C2}\underline{S}^{L}\underline{S}_{24}^{MT}\underline{S}_{32}^{MT}\underline{S}_{43}^{MT} \\ +\underline{S}^{C1}\underline{S}^{C2}\underline{S}_{23}^{MT}\underline{S}_{32}^{MT} \\ +\underline{S}^{C1}\underline{S}^{L}\underline{S}_{24}^{MT}\underline{S}_{42}^{MT} \\ +\underline{S}^{C1}\underline{S}_{22}^{MT} \\ +\underline{S}^{C2}\underline{S}^{L}\underline{S}_{34}^{MT}\underline{S}_{43}^{MT} \\ +\underline{S}^{C2}\underline{S}_{33}^{MT} \\ +\underline{S}^{L}\underline{S}_{44}^{MT} \end{array}\right] + \left[\begin{array}{l} +\underline{S}^{C1}\underline{S}^{C2}\underline{S}^{L}\underline{S}_{24}^{MT}\underline{S}_{33}^{MT}\underline{S}_{42}^{MT} \\ +\underline{S}^{C1}\underline{S}^{C2}\underline{S}^{L}\underline{S}_{22}^{MT}\underline{S}_{34}^{MT}\underline{S}_{43}^{MT} \\ +\underline{S}^{C1}\underline{S}^{C2}\underline{S}^{L}\underline{S}_{23}^{MT}\underline{S}_{32}^{MT}\underline{S}_{44}^{MT} \\ +\underline{S}^{C1}\underline{S}^{C2}\underline{S}_{22}^{MT}\underline{S}_{33}^{MT} \\ +\underline{S}^{C1}\underline{S}^{L}\underline{S}_{22}^{MT}\underline{S}_{44}^{MT} \\ +\underline{S}^{C2}\underline{S}^{L}\underline{S}_{33}^{MT}\underline{S}_{44}^{MT} \end{array}\right] - \underline{S}^{C1}\underline{S}^{C2}\underline{S}^{L}\underline{S}_{22}^{MT}\underline{S}_{33}^{MT}\underline{S}_{44}^{MT}}$$

For the full S-matrices the transfer function looks like this.

Below you see all FIRST, SECOND order loops and the only THIRD order loop. Note the alternating sign.

On top you have the path loop sum product for all paths. The third and last path do not have any non-touching loops.

The evaluation of MASON's rule is laborious and error prone. I therefore provide the free MATHEMATICA tool freeMASON.



For a given set of S-Matrices and Interconnections, freeMASON detects all paths and loops and provides a graphical control (as seen above).

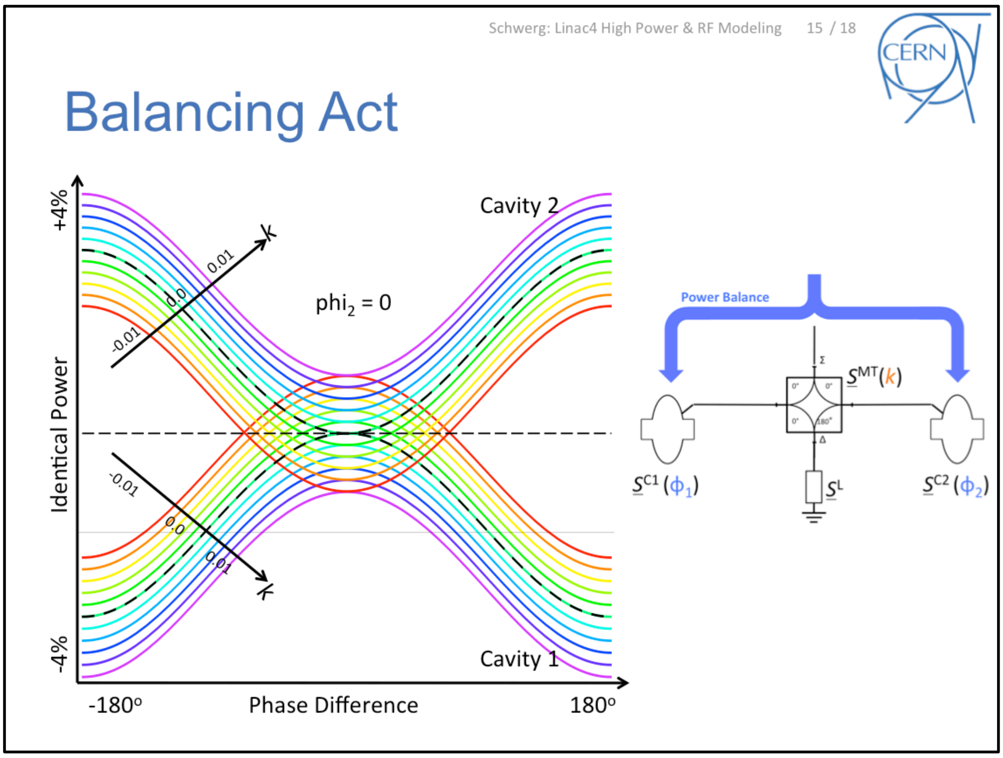
It derives the Transfer function between any two nodes of interest symbolically, i.e. it returns the analytical formula for its calculation.

The symbolic approach allows for:
- Functional evaluation such as differentiating and root-finding
- Simplifications such as FullSimplify and 0-setting
- Plotting and Optimization
- Sensitivity studies

Another noteworthy program is CSC by HW Glock which solves the problem by reducing a matrix system to its essentials…

Documentation of the approach and the presented example:
[Sch10] Nikolai Schwerg. Symbolical analysis of RF-network problems using Mason's rule, June 2010. sub-
mitted to IEEE MTT for publication.

Program:
[Sch10] Nikolai Schwerg. freeMASON 1.0. (CERN Software Package for Mathematica 7.0), June 2010. (free
download).

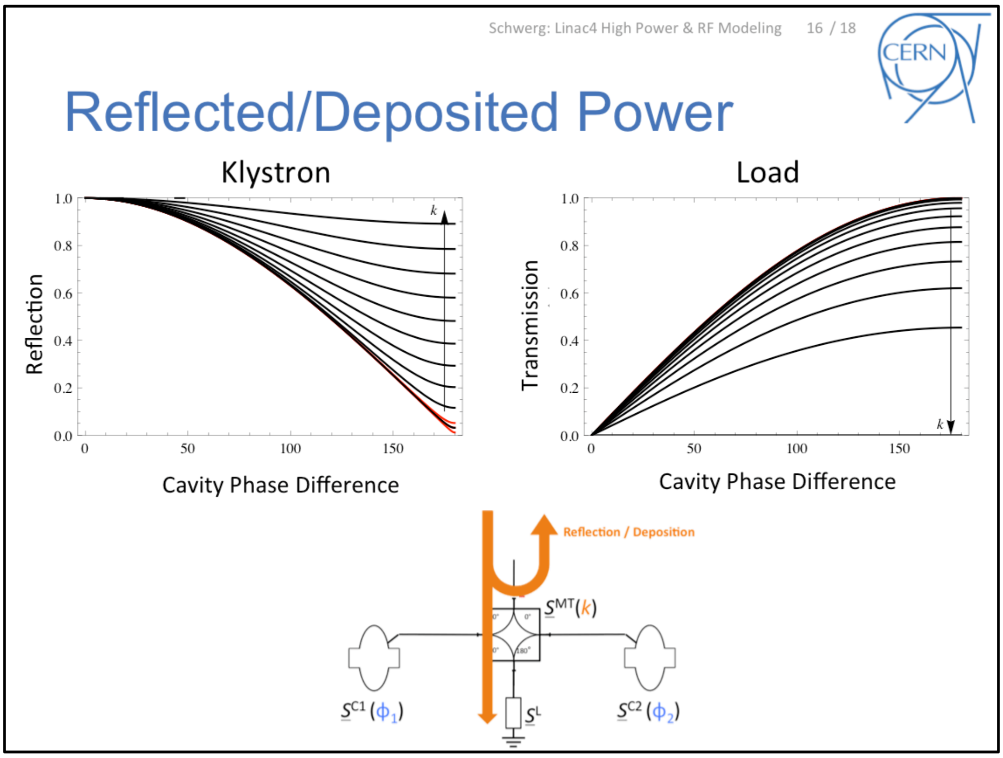


To answer the initial questions:

In the following graph we see the amplitude of the power distributed to the two cavities for different reflection phase phi1 and asymmetry k. The phase of cavity 2 is set arbitrarily to 0.

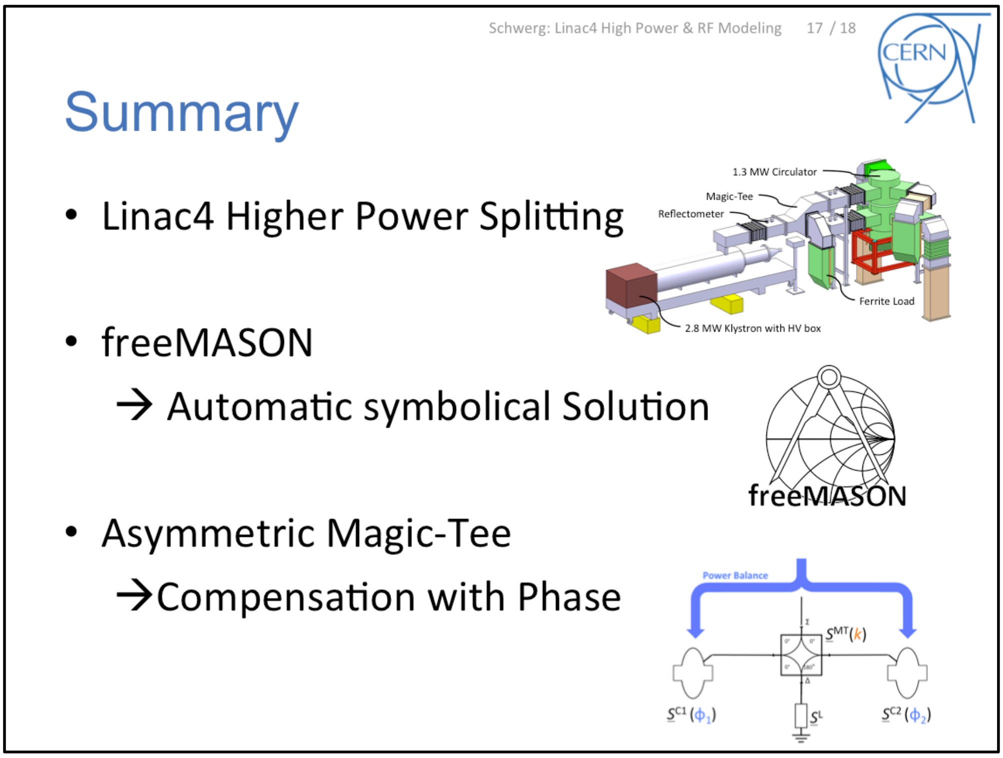
In the center we see a dashed line for a symmetric power distribution.

For k < 0 (more to cavity 1) the asymmetry can be compensated by changing the phase of the cavity 1. (If we would fix phi1 we could do so for k > 0 by changing phi2).



For much bigger variations of k we see the reflected and deposited power for various phi1 with phi2=0.

The range from the slide before is shown in red.



I would be very happy for interest in the presented program and comments on the high-power distribution scheme for Linac4.

The End

Thank you for your attention!

Talk Overview