High Performance Tool for Coupled Cavity LINAC Design

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Outlook

- Coupled Cavity Linac Design
- Circuit Model
  - Introduction
  - The model
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- Beyond Limits (How)
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  - The optimization Algorithm
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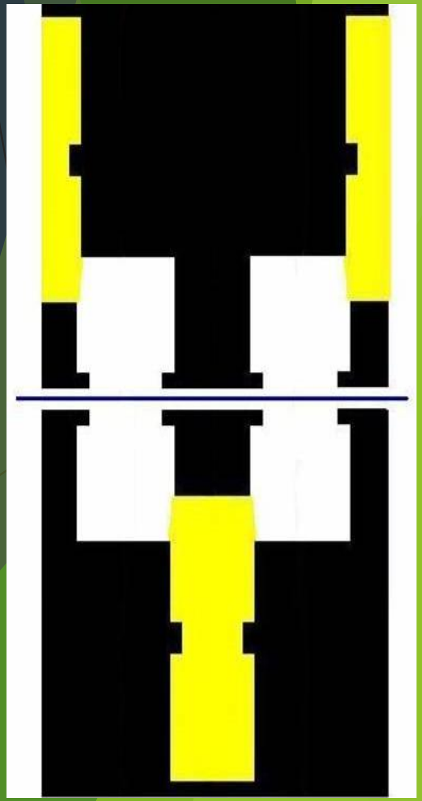
- Conclusion
- Acknowledgments

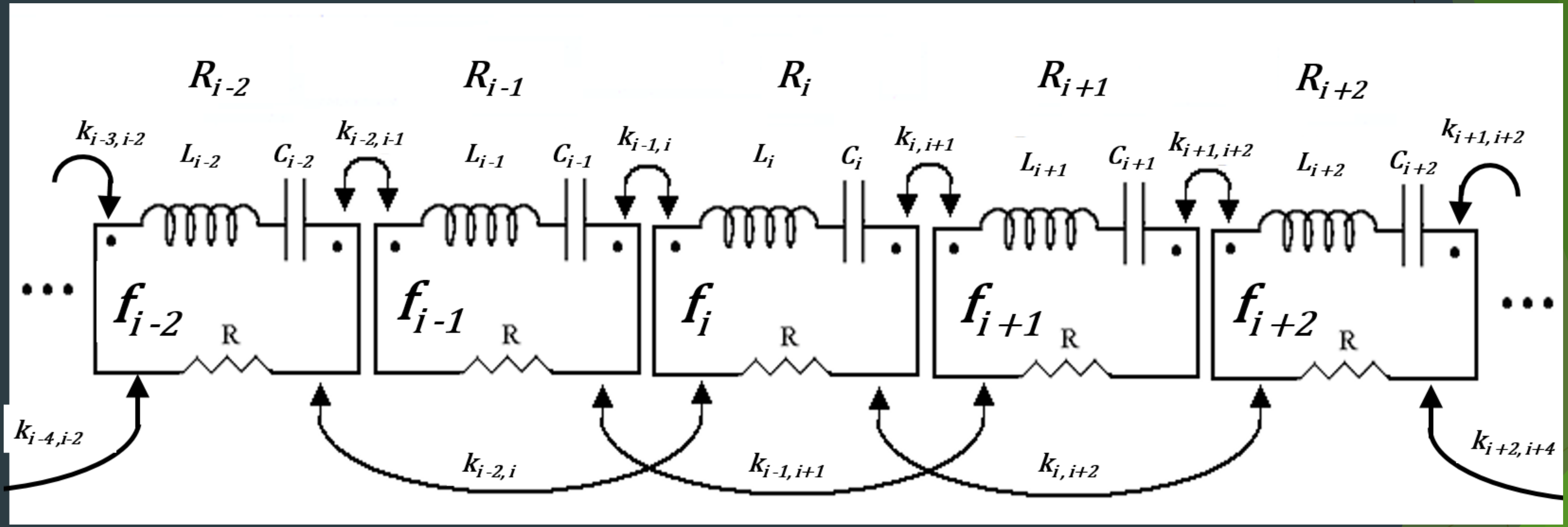
Coupled Cavity Linac Design

- In the frame of INFN – ITEL collaboration
- Commissioning of an SCL for medical applications
  - Patent and know how transfer
- While providing support we study ways to improve the technique
  - The standard procedure has serious potential for development
- Once invented, the new procedure can be rearranged to work on all the variants



Circuital model Introduction

- The Tank modes lie in a narrow bandwidth. This allows for “lumped constants” circuit representation.



- Conceived to work in “symbiosis” with the EM cads.

Circuital model

$$\bar{I} = \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_{M-2} \\ I_{M-1} \\ I_M \end{pmatrix}$$

$$\bar{\bar{X}} = \begin{pmatrix} 1-\frac{f_1^2}{F^2} & \frac{k_{1,2}}{2} & \frac{k_{1,3}}{2} & \cdots & 0 & 0 & 0 \\ \frac{k_{2,1}}{2} & 1-\frac{f_2^2}{F^2} & \frac{k_{2,3}}{2} & \cdots & 0 & 0 & 0 \\ \frac{k_{3,1}}{2} & \frac{k_{3,2}}{2} & 1-\frac{f_3^2}{F^2} & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1-\frac{f_{M-2}^2}{F^2} & \frac{k_{M-2,M-1}}{2} & \frac{k_{M-2,M}}{2} \\ 0 & 0 & 0 & \cdots & \frac{k_{M-1,M-2}}{2} & 1-\frac{f_{M-1}^2}{F^2} & \frac{k_{M-1,M}}{2} \\ 0 & 0 & 0 & \cdots & \frac{k_{M,M-2}}{2} & \frac{k_{M,M-1}}{2} & 1-\frac{f_M^2}{F^2} \end{pmatrix}$$

- Expressed as equations system, its associated matrix is easy to treat.

- The following equation describes the behavior of the whole circuit (eigenvalues -> resonant frequencies, Eigenvectors -> currents)

$$\bar{\bar{X}}\bar{I} = \bar{0}$$

Circuital model pros/cons

- The circuital model is very intuitive
- Its polynomials complexity rapidly increase with the number of cavities
- It is “easily” solved using symbolic calculus (**if cleverly manipulated**)
- The commercially available software calculus capability quickly “saturate”

Our new approach and optimization work allows to bypass the limits of this model.

Beyond limits (HoW)

- Reciprocity implies symmetry
- Expand D_{2N+1} at the symmetry points
- $D_{2N+1} \cong D^0_{2N+1}$

$$\bar{\bar{X}} \cong \bar{\bar{X}}^0$$

- $\bar{\bar{X}}^0$ is bisymmetrical
- Two sets of eigenvectors:

Symmetric and **Anti-symmetric**

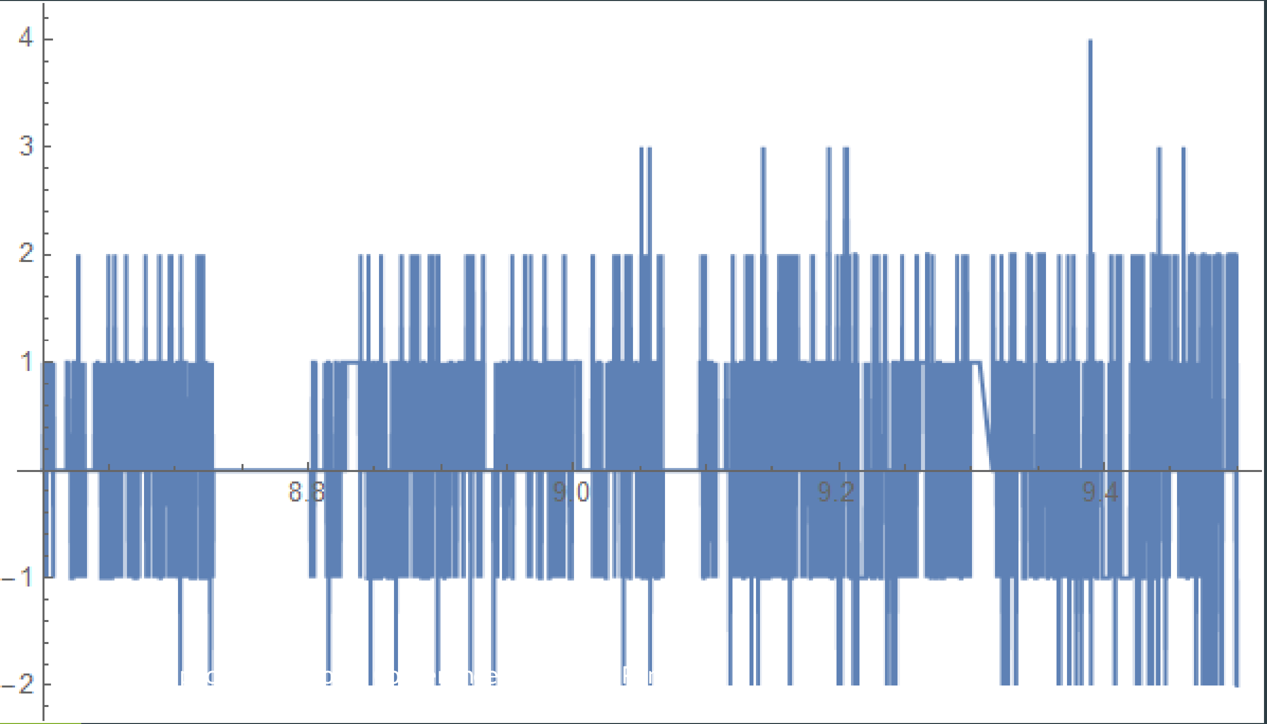
$$D^0_{2N+1} = const \cdot G_{N+1} G_N$$

$$G_{N+1} = \begin{vmatrix} 1 - \frac{f_1^2}{F^2} & \cdots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & 1 - \frac{f_N^2}{F^2} + \frac{k_{N,N-2}}{2} & \frac{k_{N,N+1}}{2} \\ 0 & \cdots & \frac{k_{N,N+1}}{2} & \frac{1}{2}\left(1 - \frac{f_{N+1}^2}{F^2}\right) \end{vmatrix}$$

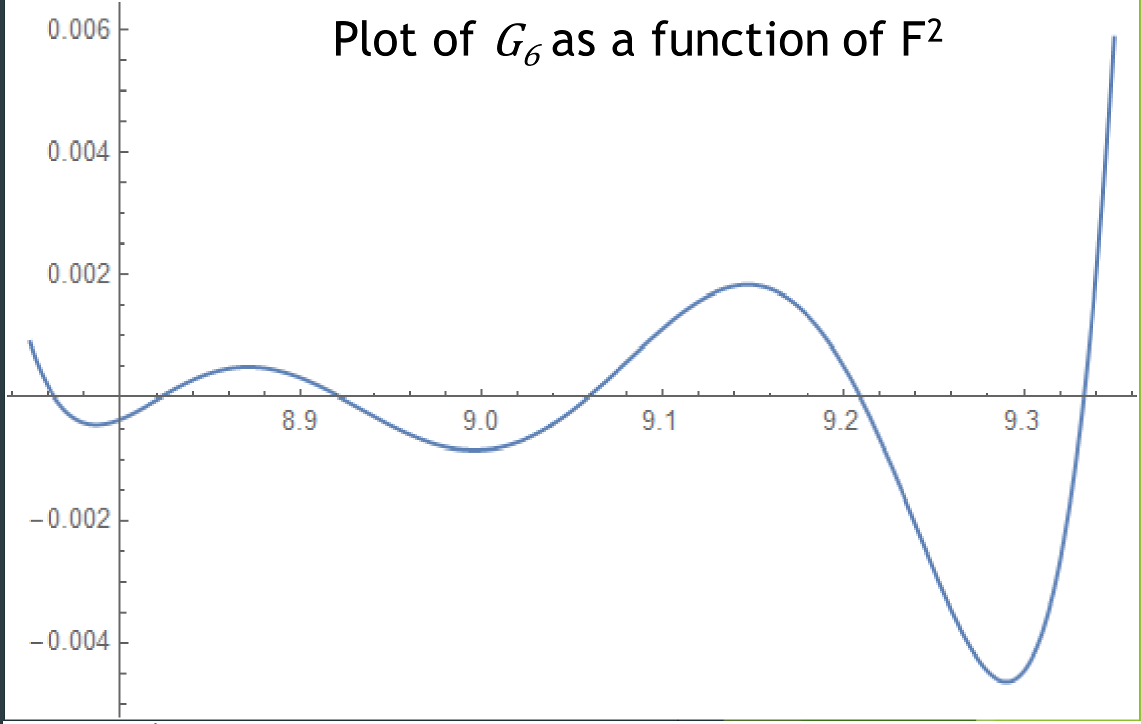
$$G_N = \begin{vmatrix} 1 - \frac{f_1^2}{F^2} & \cdots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & 1 - \frac{f_{N-1}^2}{F^2} & \frac{k_{N-1,N}}{2} \\ 0 & \cdots & \frac{k_{N-1,N}}{2} & 1 - \frac{f_N^2}{F^2} - \frac{k_{N,N-2}}{2} \end{vmatrix}$$

Beyond limits (WoW)

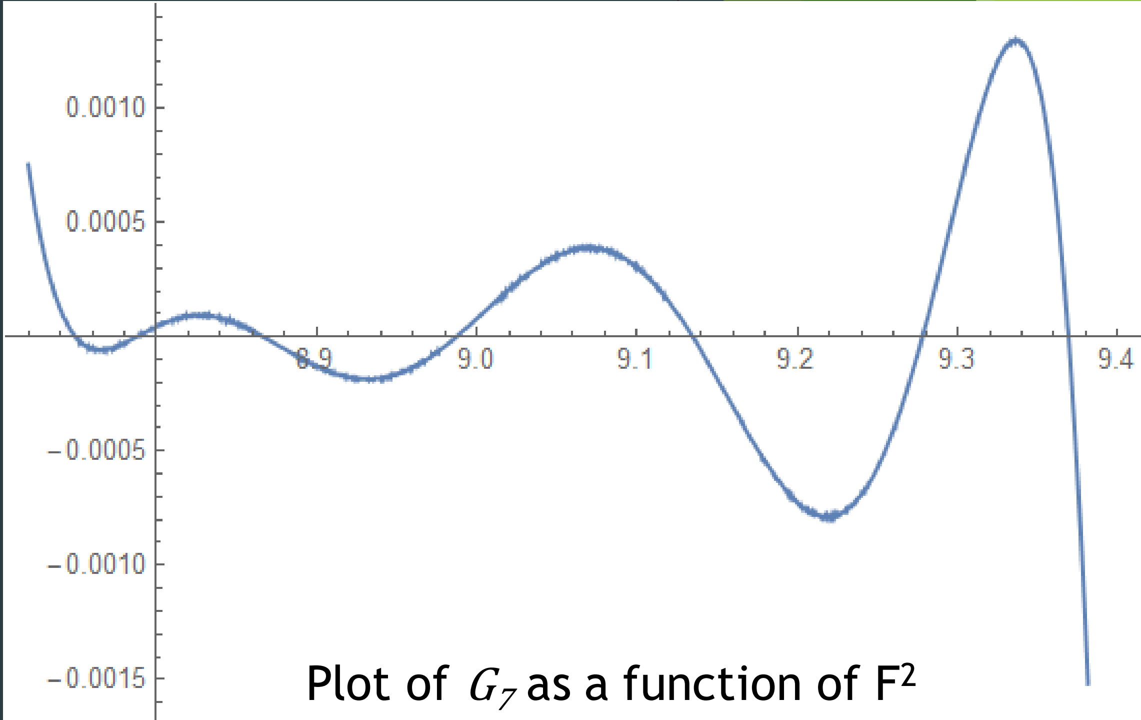
- Remarkable calculus time reduction
- Increase the cavity nr. limit (13 cavities)
- Greatly Enhanced accuracy (up to 10^{-6} GHz)



Plot of D_{13}^{0} as a function of F^2



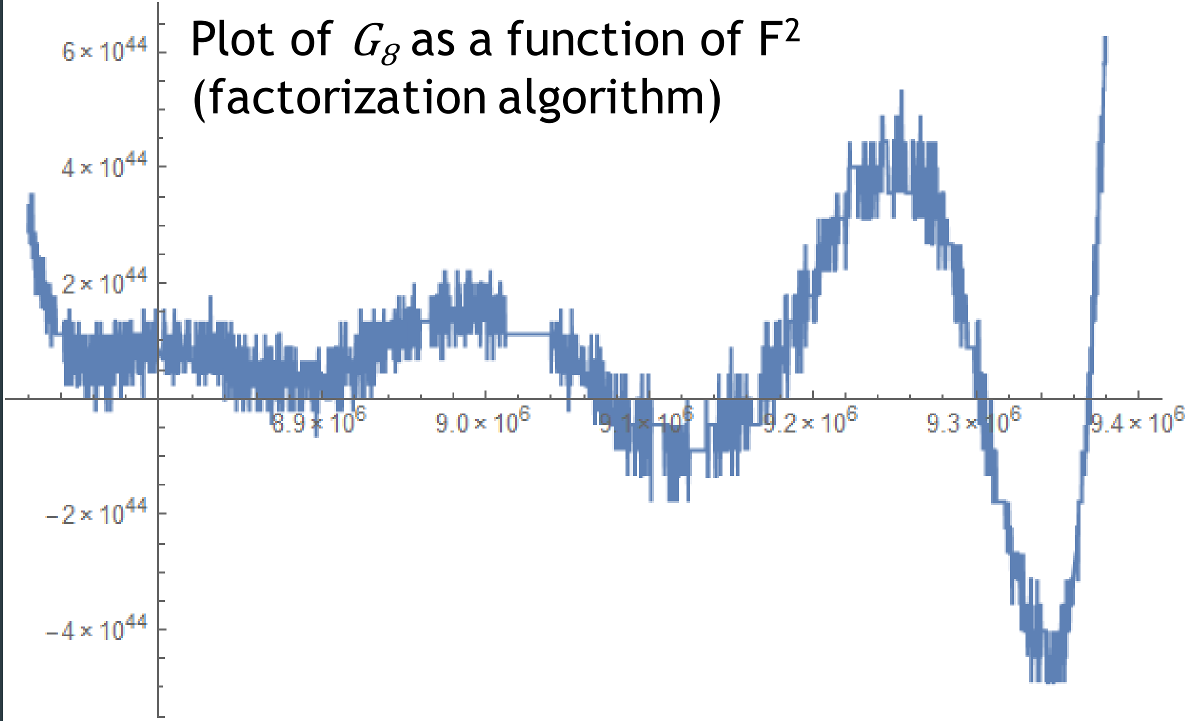
Plot of G_6 as a function of F^2



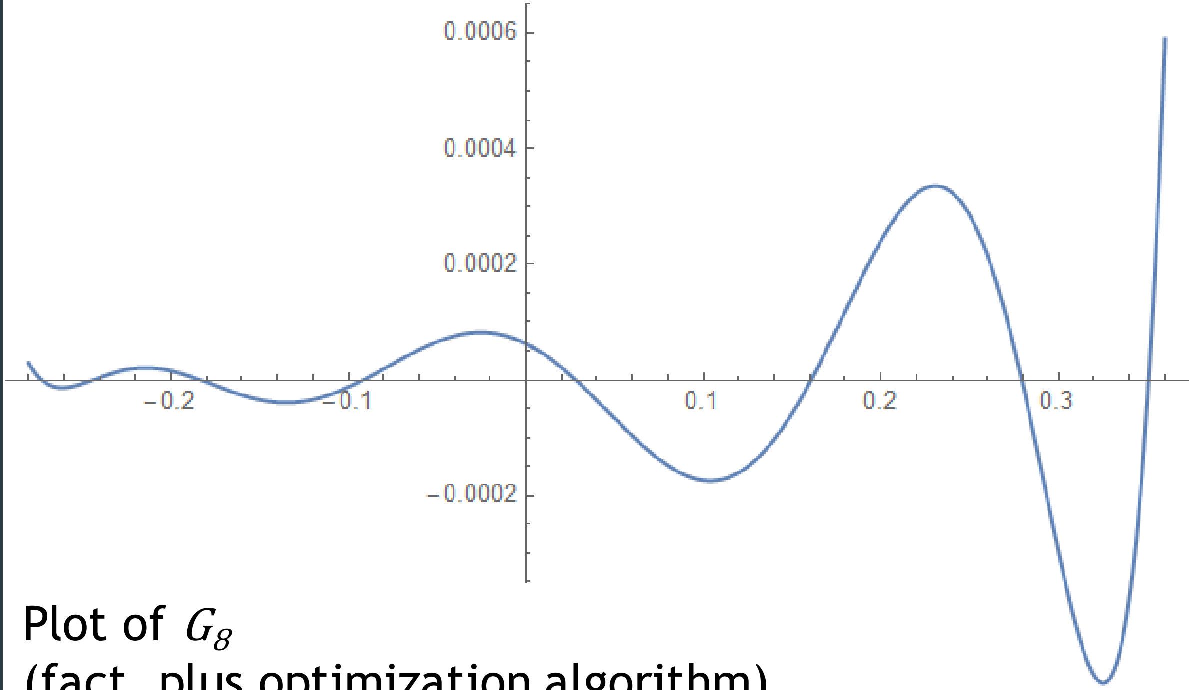
Plot of G_7 as a function of F^2

The Optimization Algorithm (The Turning Point)

- Only using the factorization algorithm, there is no hope to model a full tank.
- If embedded into an optimization algorithm the joint results are astonishing.
- The synergy of the two algorithms allowed to reach our goal.



Plot of G_8 as a function of F^2 (factorization algorithm)

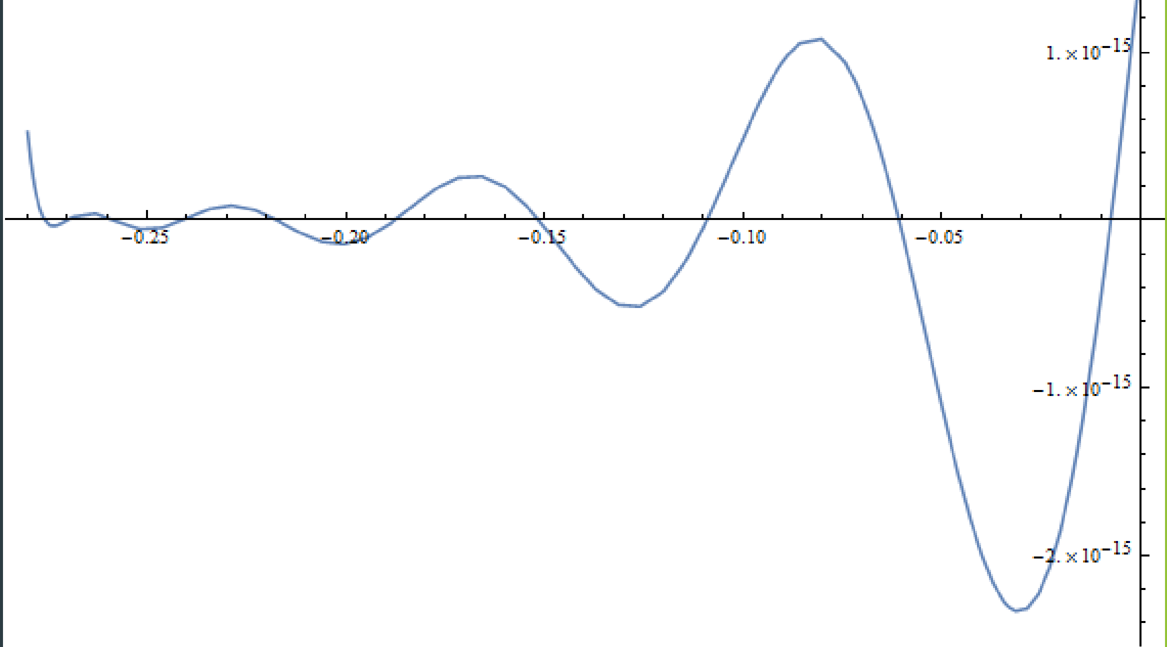


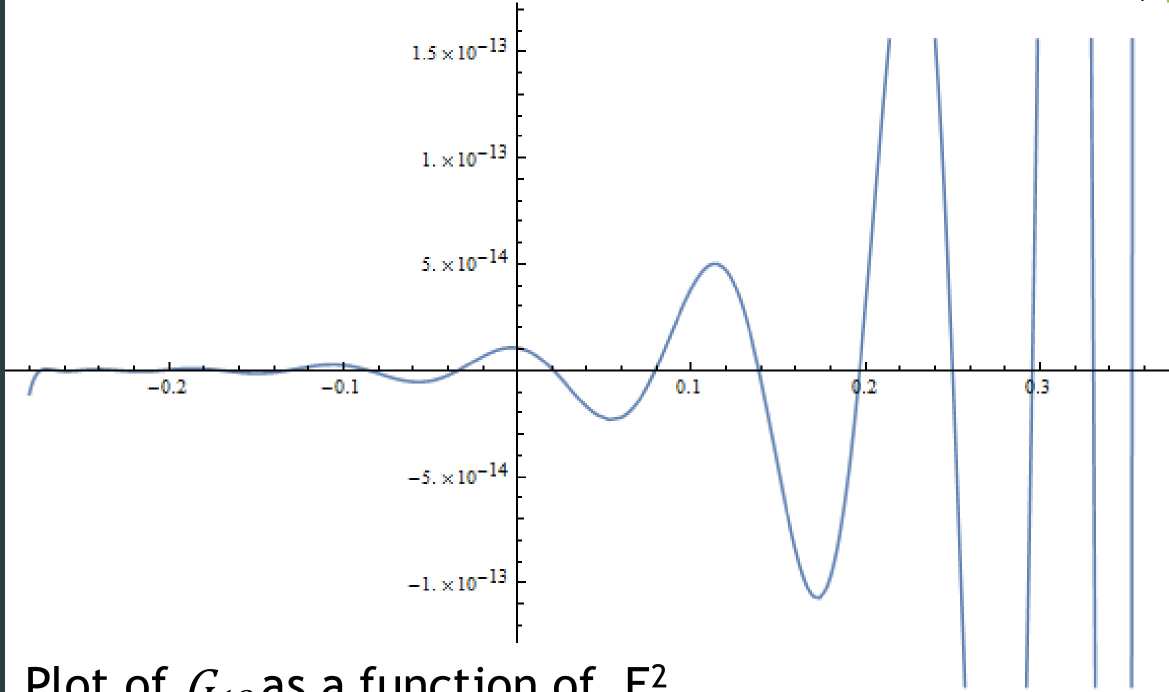
Plot of G_8 (fact. plus optimization algorithm)

The 35 cells model (SCL Full Tank)

- 35 cavity SCL tank fully represented (1st time)
- Total agreement with EM cad. simulations (Frequency agreement up to 0.01‰)
- Results provided in 1/3000 time (with respect to commercial EM cad)

Plot of G_{17} as a function of F^2 (magnified)

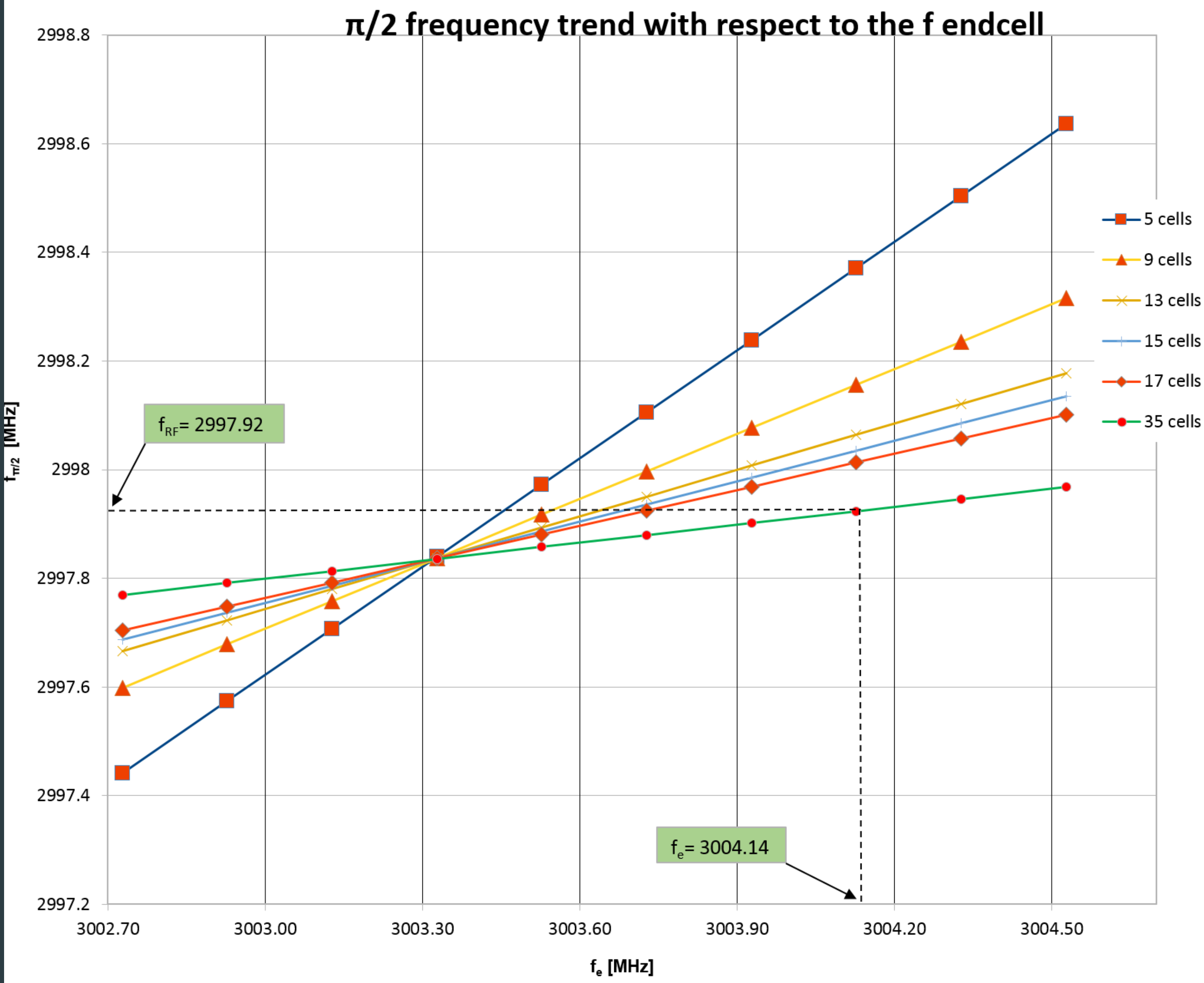




Plot of G_{18} as a function of F^2

The “Eureka” cross point (under study)

- The trends show a cross point
- A new and crucial invariant
- Turning point for Linac Design
- Deserves further studies



Conclusion

- Fully formalized, enhanced algorithm.
- Great accuracy improvement, long tanks modeled for the first time.
- Discovery of new invariant, crucial for understanding Linac behavior.
- New and interesting subject for further research and innovation

Acknowledgements

- to ITEL

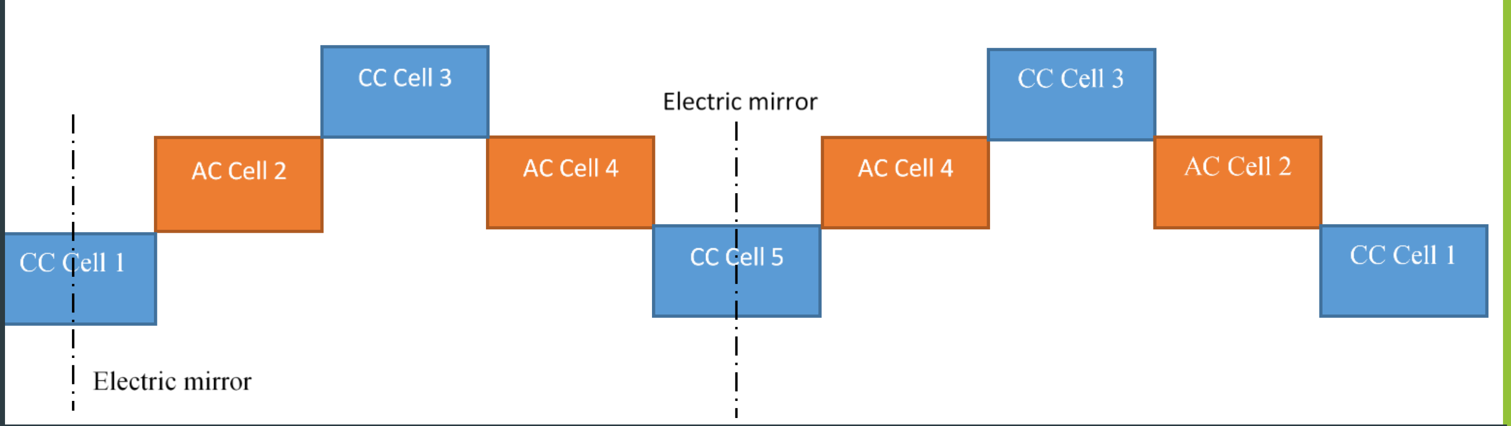
  for their kind collaboration providing MWS data.

- To OPAC

  for their invitation and support.

Thank you for your attention

The Real Deal



$$\begin{pmatrix} \frac{1}{2}\left(1-\frac{f_c^2}{F^2}\right) & \frac{k_1}{2} & \frac{k_c}{2} & 0 & 0 \\ \frac{k_1}{2} & \left(1-\frac{f_a^2}{F^2}\right)+\frac{k_a}{2} & \frac{k_1}{2} & \frac{k_a}{2} & 0 \\ \frac{k_c}{2} & \frac{k_1}{2} & \left(1-\frac{f_c^2}{F^2}\right) & \frac{k_1}{2} & \frac{k_c}{2} \\ 0 & \frac{k_a}{2} & \frac{k_1}{2} & \left(1-\frac{f_a^2}{F^2}\right)+\frac{k_a}{2} & \frac{k_1}{2} \\ 0 & 0 & \frac{k_c}{2} & \frac{k_1}{2} & \frac{1}{2}\left(1-\frac{f_c^2}{F^2}\right) \end{pmatrix}$$

- “half cell” configuration
- $D_5(k_1, k_a, k_c, f_a, f_c, F)=0.$
- From simulations we get F.
- Real Tanks are not infinite. A proper model must be introduced

The real deal (2)

$$\begin{pmatrix} 1-\frac{f_e^2}{F^2} & \frac{k_{12}}{2} & \frac{k_{a2}}{2} & 0 & 0 \\ \frac{k_{12}}{2} & 1-\frac{f_c^2}{F^2} & \frac{k_1}{2} & \frac{k_c}{2} & 0 \\ \frac{k_{a2}}{2} & \frac{k_1}{2} & 1-\frac{f_a^2}{F^2} & \frac{k_1}{2} & \frac{k_{a2}}{2} \\ 0 & \frac{k_c}{2} & \frac{k_1}{2} & 1-\frac{f_c^2}{F^2} & \frac{k_{12}}{2} \\ 0 & 0 & \frac{k_{a2}}{2} & \frac{k_{12}}{2} & 1-\frac{f_e^2}{F^2} \end{pmatrix}$$

- “full cell” configuration
- $D_5(k_1, k_c, k_{12}, k_{a2}, f_a, f_c, f_e, F)$.
- From simulations we get F.
- From half cell we get the missing parameters (i.e. k_1, k_c, f_c,)
- Found all the parameters, F is determinable for any number of coupled cavities

Designing a Coupled Cavity Linac

- Software
  - Linac
  - Superfish