Computational Needs for the Design of Superconducting Cavities

Andrei Lunin

ICAP 2012, August 19-24, 2012, Rostock-Warnemünde (Germany)
Outline

• Overlook of SC linac applications
• Specific problems of SC linac design
• SRF cavities overview
• SRF cavity EM design
• Incoherent losses & wakes
• Multipactor & Dark current
• HOM problems
• Beam loading & microphonics
• SRF cavity multiphysics simulations
• Conclusions
The SRF cavities are widely used for various applications requiring an acceleration of charged particles:

**High Energy Physics**
- **LHC**
- **CEBAF**

**Nuclear Physics**
- **ATLAS**
- **TRIUMF**
- **EURISOL**
- **SNS**
- **XFEL**
- **ERL**

**SR Sources**
- **XFEL**
- **ERL**

**UPCOMING:**
- ADS, ESS, FRIB, ILC, NGLS, Project X, …

Modern SRF cavities cover wide diapasons of particles beta (0.05..1), operating frequencies (0.072..4 GHz) and beam currents (1mA..100mA, CW&Pulsed)
Specific problems of SRF cavities

• The following aspects need to be taken into account:
  
  Acceleration efficiency
  - cavity R/Q versus beta
  - surface field enhancement factors (electric & magnetic)
  
  High Gradient pulsed operation
  - Lorentz force detuning
  
  Operation with small beam current
  - narrow cavity bandwidth & microphonics
  - mechanical stability
  
  High Order Modes (HOMs) dumping
  - incoherent effect (loss factors, cryogenic losses)
  - coherent effects (emittance dilution, cryo-losses)
  - collective effects (transverse & longitudinal beam instabilities)
  
  Field Emission
  - multipactor
  - dark current
SRF cavity is a complicated electro-mechanical assembly and consist of:
- bare cavity shell with power and HOM couplers
- stiffening elements (ring, bars)
- welded LHe vessel
- Slow and fast frequency tuners
- vacuum ports

The design of SRF cavity requires a complex, self consistent electro-mechanical analysis in order to minimize microphonics and/or Lorentz force detuning phenomena and preserving a good cavity tenability simultaneously!
The SRF cavity EM design requires precise surface electromagnetic fields computation in order to optimize the cavity shape and achieve a maximum accelerating gradient.

Mesh examples of modern EM codes

- COMSOL
- CST
- OMEGA3P
- SLANS (2D)

HFSS artificial surface mesh

Important factors:
- quality of surface mesh
- type of mesh (hex-, tetra-)
- curved surface elements
- space domain (2D, 3D)

The desirable accuracy of surface electromagnetic fields is < 1%!
SRF cavity EM design

1. Cavity shape optimization to minimize both surface $E_s$ and $H_s$ fields and maximize $R/Q$.

   - Elliptic cavity
   - Simulated shapes
   - Limiting curve
   - Spoke cavity

2. Beta optimization (optimal beta for linac sections to minimize total cost of the linac).

   - Veff (MV)
     - $\beta_{opt} = 0.10$
     - $\beta_{opt} = 0.11$
     - $\beta_{opt} = 0.12$

3. The further choice is a trade-offs between the requirements on cavity mechanical stability and surface processing.
Software for eigenmode EM simulation.

<table>
<thead>
<tr>
<th></th>
<th>OMEGA3P</th>
<th>COMSOL*</th>
<th>CST*</th>
<th>SLANS</th>
<th>HFSS*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>3D</td>
<td>2D, 3D</td>
<td>3D</td>
<td>2D</td>
<td>3D</td>
</tr>
<tr>
<td>Curved elements</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mesh type</td>
<td>Tetra</td>
<td>Tetra</td>
<td>Hex</td>
<td>Tetra</td>
<td>Quad</td>
</tr>
<tr>
<td>Complex solver</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Parallel computing</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>H-field enhancement**</td>
<td>?</td>
<td>?</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

* commercial software

** weighted residual method is applied in order to improve field calculations.
Incoherent losses introduced by radiated wakefields might be an essential part of the total cryolosses in the SC accelerating structure.

Loss factor depends strongly on the $\sigma_{\text{field}}$!

- $f_{\text{max}} \sim c/\sigma_{\text{bunch}}$
- for $\sigma_{\text{bunch}} = 50\mu$, $f_{\text{max}} < 6$ THz

Incoherent Losses & Wakes Simulation

Solve in TD
- computing wakefields and wake potentials

Solve in FD
- loss factors calculation of individual cavity modes

HE electron linac (XFEL or NGLS)

Proton linac (Project X)
Incoherent Losses & Wakes Simulation

Loss Factor Calculation Challenges (high-β structure for Project X)

**Time Domain**

- Ultra-relativistic beam (β=1)
- Weakly-relativistic beam (β<0.9)
- Highly-relativistic beam (β>0.9)

**Frequency Domain**

- Short bunches (σ_z < 1mm)
  - required memory ~ (a/σ_z)^3
  - computation time ~ (a/σ_z)^4
  - Solution: moving mesh

- Static Coulomb forces
  - E_{static} >> W_z
  - Wrong convolution: \( \int (E_s + W_z)σ_z dz \)
  - Solution: Two simulations to exclude E_s

- HOM modes
  - HOM spectrum above beam pipe cut-off freq.
  - Solution: Take modes with max R/Q, Multi-cavity simulation

- Long catch up distance ~ a^2/2σ_z
  - Solution: Indirect methods

- Direct solver require large mesh size
  - Solution: parallel computation

---

W. Bruns, GdfidL
Incoherent Losses & Wakes Simulation

Tools for a short range wakefield simulation.

<table>
<thead>
<tr>
<th></th>
<th>ABCI</th>
<th>ACE3P</th>
<th>CST*</th>
<th>GdfidL*</th>
<th>ECHO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>2.5D</td>
<td>3D</td>
<td>3D</td>
<td>3D</td>
<td>2D, 3D</td>
</tr>
<tr>
<td>Indirect methods</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Moving mesh</td>
<td>✔</td>
<td>✔</td>
<td>-</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Beta &lt;1</td>
<td>-</td>
<td>-</td>
<td>✔</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Parallel computing</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

* Commercial software
Secondary electron emission RF discharge or multipactor (MP) might be a serious obstacle for normal operation of SC cavities and couplers.

G. Romanov, FNAL, SSR1 cavity for Project X

S. Kazakov, FNAL, ILC 9-cell cavity

Cavity EM simulation
- Complex 3D multi-sections cavity model
- Precise surface fields
- SW&TW solutions
- Mesh matching with tracking module

Setup particle sources
- Advanced field emission model
- Emitters locations, numbers and phases
- Material properties

Particle tracking
- Multi-particles approach & stochastic SE emission vs. Counter Function (CF) method

Post processing
- Advanced statistics on particles
  - numbers
  - collisions
  - sec. emissions
  - dissipations
  - trajectories
Multipactor & Dark Current Simulations

High gradient SC cavity may produce electrons emitted from the surface, captured and accelerated along the linac.

Effect of dark current

- heat and RF loading of the cavity
- production of avalanches of secondary electrons
- accelerating to hundreds of MeV before being kicked out by downstream quadrupoles
- originating electromagnetic cascade showers in the surrounding materials

Challenges of dark current simulations:
- initial broad angular, space and phase distribution
- realistic model of emitters (Uniform, Gaussian, Fouler-Nord.)
- influence of SE emission
- detailed statistics on lost and accelerated particles

N. Solyak at al., FNAL
## Multipactor & Dark Current Simulations

Software for a multipactor & dark current simulation.

<table>
<thead>
<tr>
<th></th>
<th>ACE3P</th>
<th>Analyst*</th>
<th>CST*</th>
<th>COMSOL*</th>
<th>MultiPack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>3D</td>
<td>3D</td>
<td>3D</td>
<td>3D</td>
<td>2D</td>
</tr>
<tr>
<td>Emission model</td>
<td>DC</td>
<td>DC</td>
<td>DC Fowler-Nord.</td>
<td>DC</td>
<td>DC</td>
</tr>
<tr>
<td>Secondary emission</td>
<td>True</td>
<td>True</td>
<td>Furman-Pivi (True &amp; Elastic&amp; Rediffused)</td>
<td>True</td>
<td>True</td>
</tr>
<tr>
<td>Multipactor model model</td>
<td>Impact function</td>
<td>Counter function</td>
<td>Stochastic multi-particles</td>
<td>-</td>
<td>Counter function</td>
</tr>
<tr>
<td>Parallel computing</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>√</td>
</tr>
<tr>
<td>Space charge</td>
<td>√</td>
<td>-</td>
<td>√</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>Visualization</td>
<td>3D trajet., space filtering</td>
<td>3D trajet.</td>
<td>3D trajet., space&amp;time filtering</td>
<td>3D traject, space filtering</td>
<td>2D</td>
</tr>
</tbody>
</table>

* Commercial software
HOMs Properties Statistical Analysis

- Because of the fabricating tolerances and further surface processing, the actual cavity shape never matches with the theoretical shape.
- There are a natural spreads of the HOMs parameters (freq., R/Q-s and $Q_{\text{ext}}$) from cavity to cavity. We can reproduce it in the simulations using the following procedure:
  - Apply tolerances to the cell dimensions.
  - Calculating the frequency derivation (for operating mode) of each geometrical dimension for the regular and end cells.
  - Tune the individual cell frequency by changing its period (exactly how the tuning machine is working!) at the stage of the full structure geometry creation.
  - Simulate the derived 5-cell structure (check the operating mode flatness!). Repeat the simulation 30-50 times to get the statistics.

- There are trapped HOMs exist in the cavity spectrum above the cut-off frequency on a beam pipe!
- For the accurate result one has to simulate the chain of at least 3 randomly generated structures with mechanical tolerances and take into account the stainless steel bellows between the structures.

Map of the electric fields in the chain of 3 structures connected with bellows
HOMs Properties Statistical Analysis

**Monopole Modes Frequencies Variance**

- Frequency, [GHz]
- Frequency variance, [Hz]

**5th Monopole Passband Histograms**

- Frequency, [MHz]

**Monopole Modes Q_{ext} Variance**

- Mode Number
- Q_{ext}, [Ohm]

* 650 MHz, beta= 0.90 Project X structure with ± 0.2 mm tolerance applied
HOMs Properties Statistical Analysis

Based on the predicted deviations of monopole HOMs frequency, $Q_{\text{ext}}$ and $R/Q$, we used $10^7$ random cavities in order to estimate the probability of RF losses per cryomodule and the effect of longitudinal emittance growth in Project X linac.

The results of HOMs study allow to exclude HOM couplers/dampers!
Microphonics is a cavity mechanical deformations driven by external forces such as the pressure fluctuations in a He-vessel and result unfavorable RF phase errors.

Microphonics study requires self consistent electro-mechanical simulations!

(M. Hassan, Fermilab)
The conception of moving mesh allows to exclude the mesh errors and achieve excellent accuracy (~1Hz/Torr) in df/dp analysis!

Using reinforcing and stiffening elements are very important to reduce df/dp.
Lorenz Force Detuning (LFD) is the cavity mechanical deformations caused by a pressure load of the Lorenz forces from EM-fields in the cavity. It significantly distort the pulsed operation of SC cavity at high accelerating gradient.

- The LFD analysis require transferring the solution for EM-fields to mechanical solver.
- The stiffening rings allow to compensate deformations of electric and magnetic fields and, thus, give a low LFD coefficient.
- The accurate LFD simulation require complete mechanical model including He-vessel and slow tuner.
The thermal impedance of HOM coupler may cause a thermal instabilities (quench) in the superconducting cavity.

- The RF-thermal analysis require transferring the solution for EM-fields to thermal solver.
- The multiphysics effects include nonlinear material properties at the superconducting temperature.
- The parallel RF & thermal solvers implementation allows to perform accurate and fast analysis.
## SRF Cavity Multiphysics Simulations

Software for a coupled multiphysics problems analysis

<table>
<thead>
<tr>
<th>Feature</th>
<th>ACE3P</th>
<th>COMSOL*</th>
<th>CST*</th>
<th>ANSYS*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>3D</td>
<td>2D, 3D</td>
<td>3D</td>
<td>3D</td>
</tr>
<tr>
<td>Coupled RF &amp; mechanical (df/dp)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>LFD</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>√</td>
</tr>
<tr>
<td>Coupled RF &amp; Thermal</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Parallel Computing</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Moving Mesh</td>
<td>-</td>
<td>√</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nonlinear effects</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>√</td>
</tr>
</tbody>
</table>

* Commercial software
Conclusions

• The design of SRF cavity has to satisfy a complex relationship between the accelerator requirements, cryogenic effects and the cryomodule structure.

• Modern state of the art software for multiphysics analysis allow to simulate various problems related to the design of SRF cavity and find reliable engineering solutions.

• The study of these effects leads to specification of SC cavity and cryomodule and can significantly impact on the efficiency and reliability of the superconducting linac operation.
I am very grateful to Slava Yakovlev, Gennady Romanov and Timergali Khabiboulline for useful discussions

to Mohamed Hassan, Peter Ostroumov, Ivan Gonin and Nikolay Solyak for providing input and plots

and all the people who performed actual simulations