Technology Development of High-gradient C-band based Accelerators

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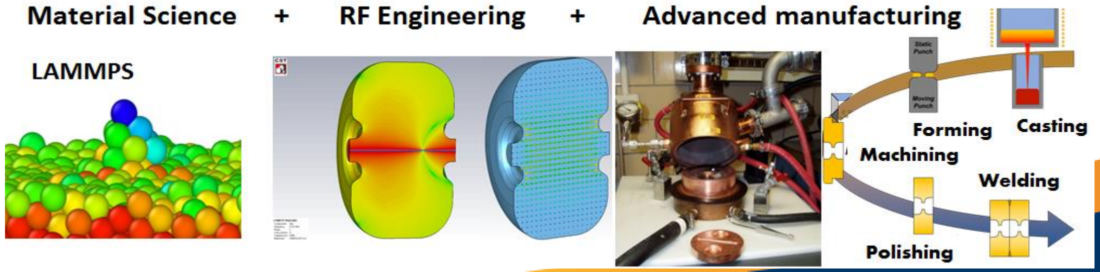

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Outline

Work completed since the last meeting

- Fully funded 3-year program (until Sept. 2022)
- Established molecular dynamics tools for RF-breakdown studies
- Established relevance of C-band as best frequency for LANL applications
- Acquisition and installation of C-band klystron and test-stand

Present and future plans

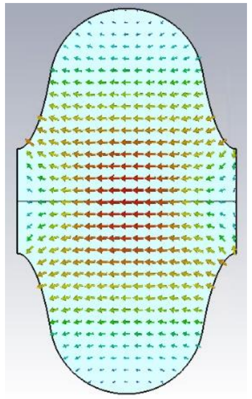
- Develop better understanding of RF-breakdown (see talk by Danny Perez)
- Develop C-band structures for gradients at or above 100 MV/m (β=1.0)
  - Better materials and fabrication techniques
  - Cryo-cooled operation at 77K
- Develop C-band structures for proton applications (e.g. pRad)
  - Energy and (β) range: 140 MeV to 20 GeV (0.5 to 1.0)
  - Moderate gradient up to 40 MV/m
- Develop RF-source technology to higher peak power, flexible RF-pulse format

Molecular Dynamics Simulation Tools

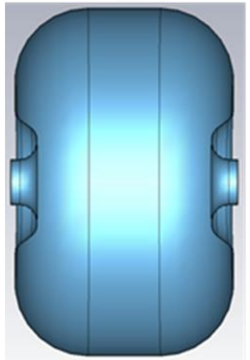
- Most accurate
  - Density Function Theory (DFT), quantum physical approach
  - Slow, only small ensembles of particles, not good for dynamic effects
- Manageable
  - Classical Molecular Dynamics (MD) – with modifications
  - Faster, more relevant ensemble sizes, multiple grains, dynamics up to a few μs
- What is missing
  - Electromagnetic (EM) Forces are insufficient to create breakdown precursors
  - EM model does not obviously lead to “low” breakdown limits
- Effects that have to be included
  - Thermal Fatigue
  - Plasma forming at nano-tips (e.g. Flyura Djurabekova, Univ. of Helsinki)
  - Propagation of defects to the surface (e.g. Yinon Ashkenazy, Hebrew Univ. of Jerusalem)

C-band Relevance for LANL Applications

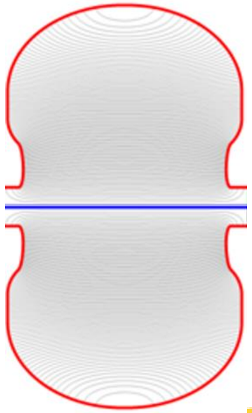
- RF performance metrics for RF structures (efficiency, gradient and multi-bunch decoupling) favor higher frequency (**C** and X).
- Coupling between an RF structure and the transported beams (good and bad wake fields) favor lower frequency (S and **C**).
- Ease of fabrication and RF-transport losses also favor the lower range (S and **C**).
- C-band (5.712 GHz) is the only established frequency that has favorable properties on all these criteria.



a/λ = 0.24	Units	S-band	C-band	X-band
Shunt Impedance	MΩ/m	47	**66**	**94**
Longitudinal Wakes	V/pC	**11.7**	**16.1**	**22.1**
Energy Change	@ 1 GeV	**1.1%**	**1.5%**	**3.4%**
Transverse Wakes	V/pC/m	**12.2**	**67.1**	**366.3**
Deflection at 1 μm	kV	**0.12**	**0.64**	**3.50**



a/λ = 0.10	Units	S-band	C-band	X-band
Shunt Impedance	MΩ/m	85	**120**	**170**
Longitudinal Wakes	V/pC	**26.5**	**36.4**	50.4
Energy Change	@ 1 GeV	**2.5%**	**3.5%**	7.7%
Transverse Wakes	V/pC/m	**155**	**835**	4420
Deflection at 1 μm	kV	**1.5**	**8.0**	67.4

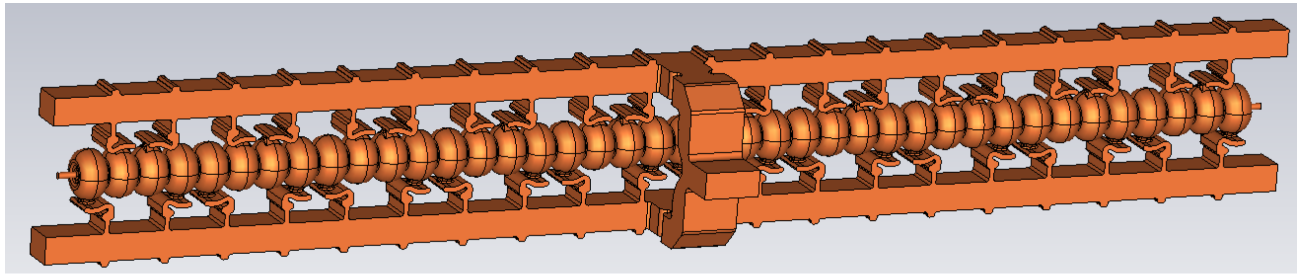


a/λ = 0.04	Units	S-band	C-band	X-band
Shunt Impedance	MΩ/m	86	**121**	**172**
Longitudinal Wakes	V/pC	**45.8**	**64.3**	90.5
Energy Change	@ 1 GeV	**4.4%**	**6.1%**	13.8%
Transverse Wakes	V/pC/m	**306**	**1683**	9037
Deflection at 1 μm	kV	**2.93**	**16.1**	86.4

C-band Engineering Research Facility (CERF-NM)

- Development of C-band technology is a high LANL priority
- DDSTE and the ALD for Physical Sciences invested $1.3M into purchase/installation of a 50 MW peak power klystron
- Klystron supports our 3-year effort for sample and cavity testing
- Complimentary efforts, mostly in collaboration with UCLA and SLAC (e.g. on injector, diagnostics, RF-sources, C-band RF-components) to develop facility into electron beam test accelerator
- Collaborative proposals on compact FELs, cryogenically cooled RF-structures, reduced β-structures for medical, isotope production or pRad

High-Gradient Structures for Electron Beams



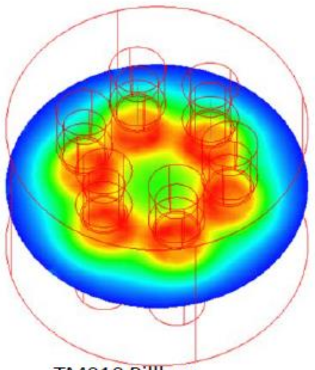
- Material Science effort
  - better understanding of RF-breakdown
  - Are there better copper alloys with lower RF-breakdown probability?
- RF-structures
  - Design and test reference structures from regular copper (SW, waveguide manifold coupling)
  - Test cavity for sample testing – we try to do more than DC testing
  - Develop new Rf-structures based on cryo-cooling copper (77K)
- Advanced manufacturing
  - Implement low-temperature machining, forming, joining and cleaning techniques
  - Fabrication infrastructure: methods that do not compromise the properties of source materials
  - In-house fabrication of newly developed RF-resonators

High Gradient Structures for Proton Beams

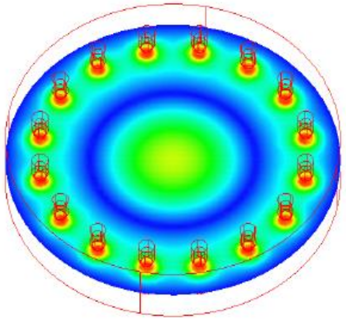
- Leverage Material Science and Advanced Manufacturing work
- Structure and beam dynamics simulations to determine suitable start energy for C-band structures – decide velocity grading scheme
- Final pRad concept might have a S-band front end
- Test reduced β-structures in collaboration with SLAC
- Design, build and test multi-cell resonators
- Optional beam tests at LANSCE
- Develop technology use cases for technology
  - pRad
  - Isotope production
  - Medical accelerators

Concepts for new C-band Source Technology

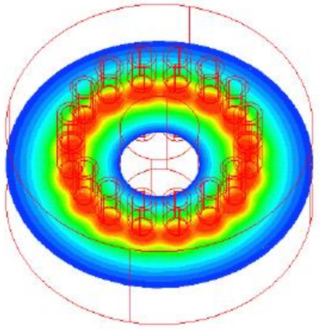
- Standard C-band klystron configurations are limited
- We need higher power, flexible pulse formats and longer pulses
- Path to MBKs has challenges (e.g. over-moding)
- Plan to develop proposal on collaborative effort with SLAC
  - Better modulator/HV technology
  - High current density cathodes **(Nanocomposite Scandate Tungsten (NST) cathodes)**
  - Multi-beam klystron development



TM010 Pillbox
Scales with f; at 5.7 GHz
too small



TM020 Pillbox
Large, but too much stored
energy in center



TM010 Toroidal
Large, strong beam
interaction, modes at higher f

3-year Effort

	FY 2020	FY 2021	FY 2022
Materials Science	Tools/Breakdown Study Thermal effects/defects	Design copper alloys	Design copper alloys Refine models
RF Engineering	Benchmark resonators Sample Tests Cryo-cooling	β=1 Cells from new alloys β<1 Cells from new alloys	β=1 multi-cell resonators β<1 multi-cell resonators
Advanced Manufacturing	Develop methods and tools manufacture samples	build single cell resonators evaluate methods	build multi-cell resonators use best methods
Experiments	Condition klystron Condition test stand Test cavities for SLAC/LANL	Test single cells Upgrade RF-power Tests for collaborators	Test multicells cells Tests for collaborators
Extended technologies	Collaboration with UCLA (cFEL, injector)	New RF sources Injector install	First beam experiments

Acknowledgements

- LANL DDSTE, ALDPS (infrastructure investment)
- LANL Accelerator, Theory and Fabrication divisions (multidisciplinary approach)
- LANL LDRD program
- RF source group at SLAC
- PSI – SwissFEL