

MARCH 3-4, 2026

NCRF GARD RF ROADMAP UPDATE

Community Synthesis and
Forward-Looking Challenge Areas

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WHY WE ARE HERE

2026 GARD RF Roadmap

- 2017 GARD RF Roadmap → nearly a decade old
- New 2023 P5 report
- Evolving accelerator landscape
- DOE requested updated 10-year roadmap
- NCRF is one of four RF subtopics (w/ SRF, RF sources, LLRF)



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Slide 2

ES1 I suggest we put a couple slides here summarizing the 2017 GARD RF Roadmap.
Evgenya Simakov, 2026-02-18T16:52:41.404

WHAT THIS TALK WILL DO

NCRF Community synthesis — not prioritization.

1. Brief review of 2017 RF roadmap
2. Summarize themes from the January virtual meeting
3. Identify community-derived “Challenge Areas” (3-5 areas desired)
4. Propose short/mid/long-term milestones
5. Highlight DOE and industry alignment



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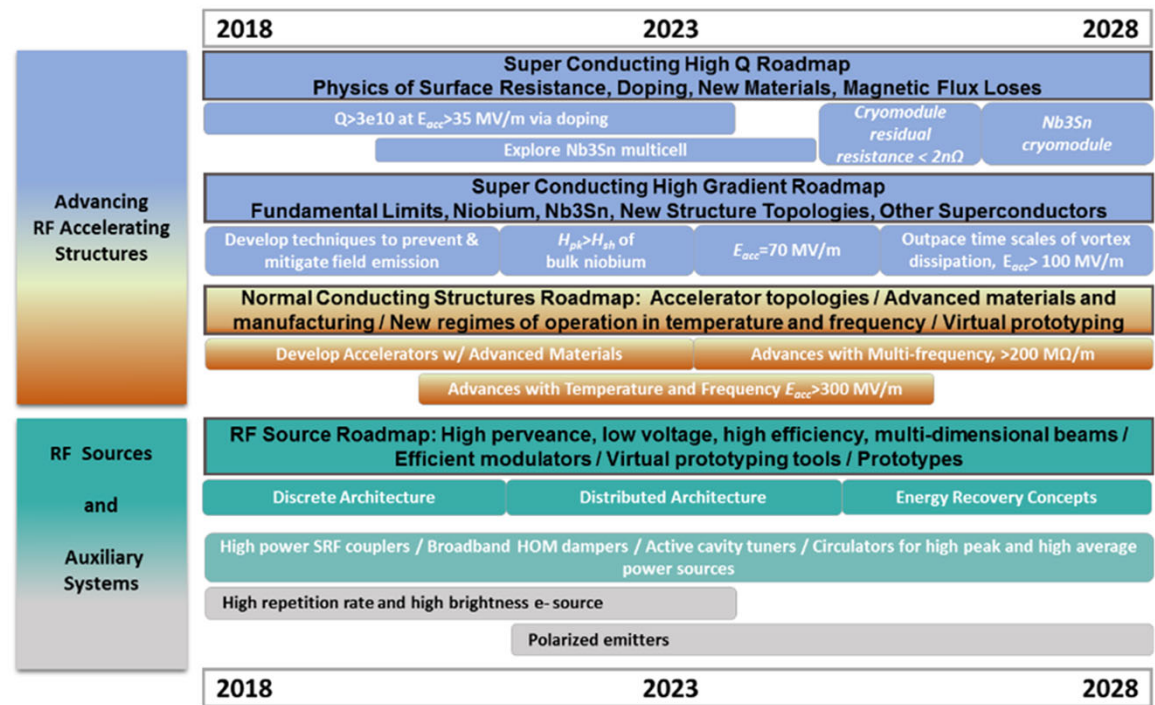
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2017 GARD RF ROADMAP

Focus on improving accelerator structures, RF sources, and auxiliary systems ES1



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Slide 4

ES1 I would say "breakdown modeling and development of predictive capabilities"
Evgenya Simakov, 2026-02-18T17:34:29.691

2017 DECADAL ROADMAP FOR NCRF STRUCTURES

Focus on pushing the gradient and acceleration efficiency

ES1

Normal Conducting Structures Roadmap

| Year: | 2018 | 2023 | 2028 |
|---|--|--|-----------------------------------|
| | Accelerator topologies / Advanced materials and manufacturing / New regimes of operation in temperature and frequency / Virtual prototyping | | |
| | Develop Accelerators w/ Advanced Materials | Advances with Temperature and Frequency | Advances with Multi- Frequency |
| Goals: Gradient Impedance Efficiency | 100 MV/m 120 MΩ/m >20% | 150 MV/m 150 MΩ/m >30% | >300 MV/m >200 MΩ/m 60% |



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Slide 5

ES1 I would say "breakdown modeling and development of predictive capabilities"
Evgenya Simakov, 2026-02-18T17:34:29.691

5 SPECIFIC GOALS FOR NCRF STRUCTURES

The roadmap aims for gradients higher than 300 MV/m, shunt impedance greater than 200 MΩ/m, and RF-to-beam efficiency of 60% by the end of the decade.

- Design new, simple-to-fabricate hard copper structures with integrated damping.
- Demonstrate wakefield suppression in these novel structures.
- Determine the impact of frequency and temperature on the high gradient limit.
- Develop better understanding of the tradeoffs in operating frequency and temperature.
- Demonstrate multi-frequency accelerating structures.



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Slide 6

ES1 I would say "breakdown modeling and development of predictive capabilities"
Evgenya Simakov, 2026-02-18T17:34:29.691

2017 GARD RF ROADMAP

Progress made

- 300 MV/m Gradient? (400 MV/m short pulse RF)
- 60% RF to beam efficiency?
- Shunt Impedance?
- Distributed coupling?
- Etc?



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Slide 7

ES1 I would say "breakdown modeling and development of predictive capabilities"
Evgenya Simakov, 2026-02-18T17:34:29.691

SUMMARY OF NCRF RF ROADMAP VIRTUAL MEETING (15 TALKS)

1. PROJECT-DRIVEN NEEDS (6 TALKS)
2. FUNDAMENTAL RESEARCH (4 TALKS)
3. STRUCTURE DEVELOPMENT (5 TALKS)



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Slide 8

ES1 7 Project driven, 4 Fundamental, 5 Development talks
Evgenya Simakov, 2026-02-18T16:53:32.076

PROJECT-DRIVEN NCRF THEMES

Themes for NCRF accelerating systems & structures

- Reliability (all)
- High-gradient (LANSCE, BES)
- Magnetic-field operation (Muon Collider)
- HOM damping (EIC, FCC-ee, BES)
- High-brightness sources (BES)
- Compact (Industry, BES)
- Low-cost (all)



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1. FCC-EE INJECTOR LINACS

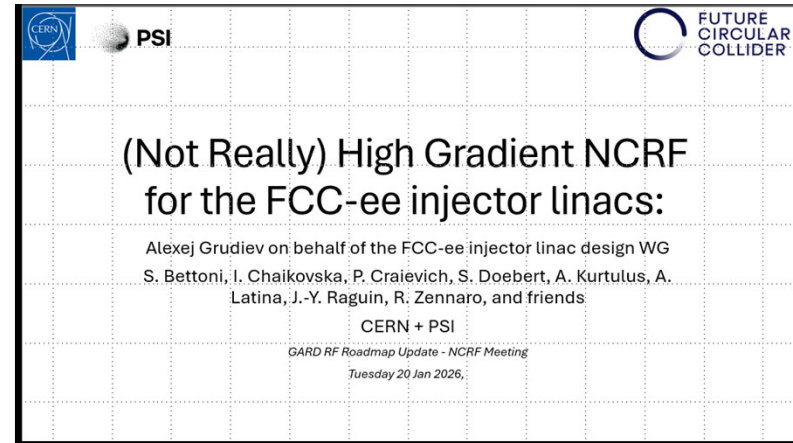
Theme: TDR-driven optimization + RF efficiency improvement

Key needs:

- Reliable S-band accelerating structures (new S-band frequency of 3005.9 MHz to be in resonance with the collider ring)
- Gradients 13.3 -21.1 MV/m, shunt impedance 71-81 MΩ/m
- Beam dynamics and HOM suppression (4 × 5 nC bunches, 25 ns spacing)
- >70% efficiency of RF power sources (multi-beam klystrons)
- TDR-level prototyping of major RF components

Program status:

- Mature engineering toward TDR



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2. MUON COLLIDER IONIZATION COOLING CAVITIES

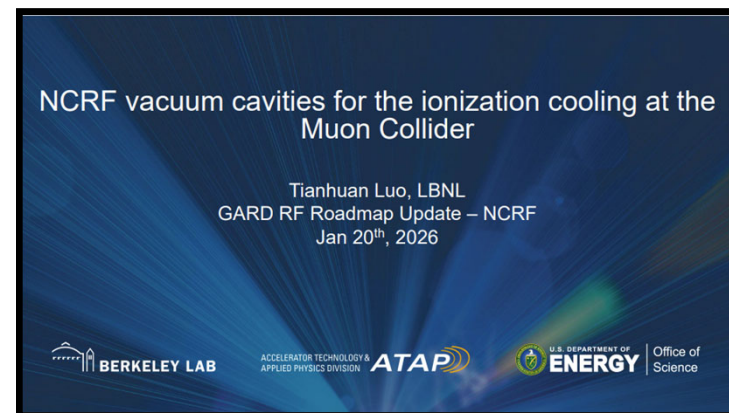
Theme: High-gradient NCRF operation in strong magnetic fields

Key needs:

- 200–800 MHz normal-conducting RF cavities
- Operation at ≥ 25 MV/m accelerating gradient in multi-Tesla solenoidal magnetic fields
- Higher gradient is preferred for the beam cooling, beam focusing, and beam loading compensation
- Geometry and materials mitigation strategies (e.g., distributed coupling, Be, cryogenic operation)

Program status:

- Conceptual design stage; R&D frontier



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3. BES ACCELERATORS

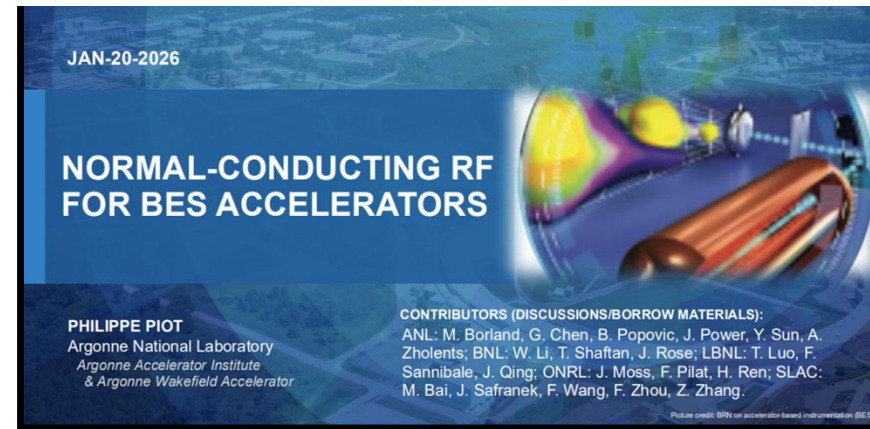
Theme: Higher surface fields, higher rep-rate, higher brightness

Key needs:

- High-gradient photoinjectors for increased beam brightness (400 MV/m on the cathode was demonstrated with a short pulse)
- High repetition rates (kHz) is an important need
- High-gradient cavities for fast beam manipulation and diagnostics
- Enhanced phase-space control and beam multiplexing via tailored field topologies
- High-frequency (sub-THz) structures for compact UED, radiation sources, and compact accelerator concepts

Program status:

- Facility upgrade and capability expansion



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4. EIC HADRON RING RF

Theme: High-current storage-ring RF systems + multiphysics engineering

Key needs:

- Low-frequency (25–200 MHz) NCRF cavity systems
- Surface fields 7-14 MV/m, close to Kilpatrick limit
- High-current beam stability with strict impedance control, lower R/Q helps with beam loading
- HOM/FMD damping and power coupler performance
- Component prototyping and system integration toward project milestones

Program status:

- Project advancing toward construction milestones; engineering validation and reliability are central



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5. LANSCE BOOSTER

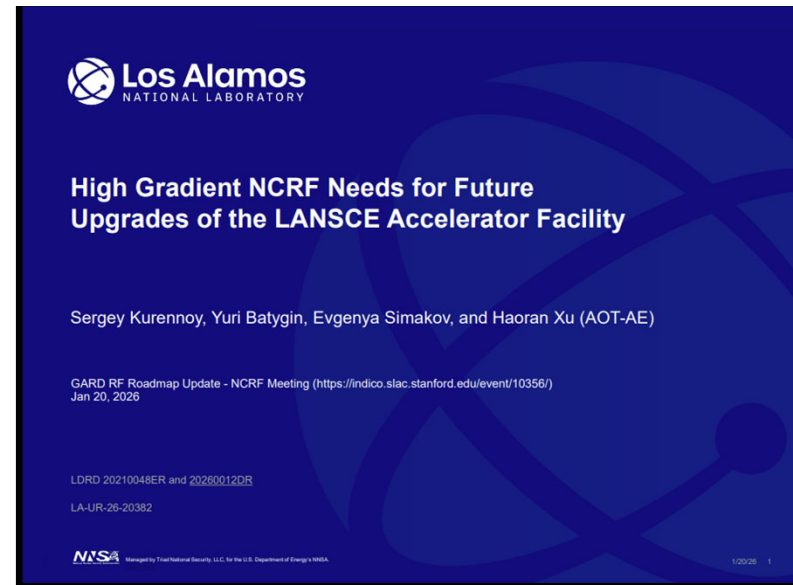
Theme: High-gradient proton linac architecture + RF delivery constraints

Key needs:

- High-gradient S-band and C-band structures adapted for proton velocities (25 MV/m at S-band and 40 MV/m, potentially up to 100 MV/m at C-band)
- Variable pulse structure or long-pulse (2-50 μ s)
- High shunt impedance desired (currently 70-80 M Ω /m)
- Distributed coupling linac architecture
- RF power delivery and pulse format optimization

Program status:

- Upgrade concept under study; architecture and RF delivery require validation



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6. INDUSTRIAL & COMPACT SYSTEMS

Theme: Cost-aware NCRF innovation

Key needs:

- High-gradient is not always the primary driver (commercial systems operate at 10-20 MV/m for the final energies below 10 MeV, higher gradient leads to higher cost)
- To achieve energies above 100 MeV (sometimes 1 GeV) within a limited footprint, higher gradients may be desired: VHEE, compact light sources, isotope production.
- Reliability and cost dominate
- RF source cost is a major limiter

Program status:

- Application-driven development; cost and reliability dominate adoption

Use of High Gradient NCRF Accelerating Structures in Small Industrial Accelerator Systems

GARD RF Roadmap Update - NCRF Meeting
January 20, 2026

Sergey V Kutsaev



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CROSS-CUTTING THEMES FROM PROJECTS

Across FCC-ee, MuC, BES, EIC, LANSCE, and Industry:

- Beam dynamics control (wakefields, impedance, phase-space manipulation)
- RF power cost and efficiency
- Higher accelerating gradients across multiple frequency regimes
- Advanced cavity architectures (distributed coupling, tailored field topologies)
- Increased need for prototyping, validation, and simulation capability
- Materials and surface performance under extreme operating conditions



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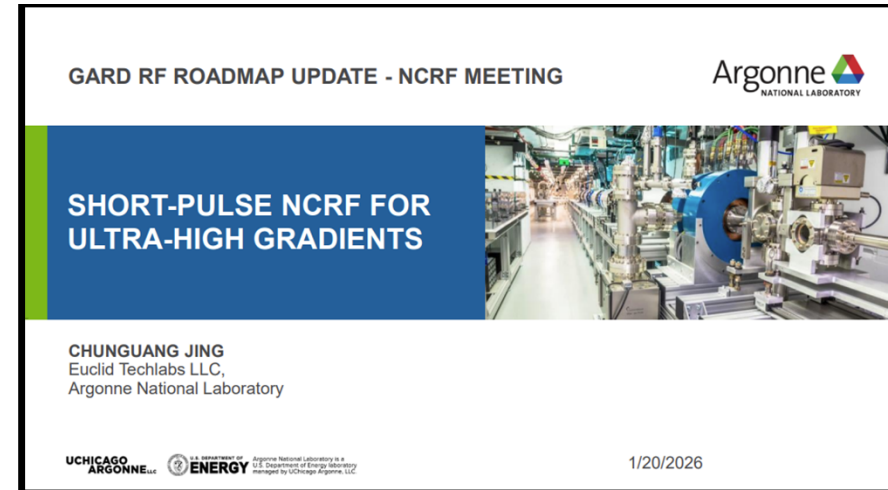
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7. SHORT-PULSE ULTRA-HIGH GRADIENT

Research

Key findings:

- 300–400+ MV/m accelerating gradients demonstrated at few-ns pulse lengths
- Modified breakdown scaling behavior in the short-pulse regime
- Evidence for Beam-Insensitive Acceleration Regime (BIAR) physics
- Recent results motivation exploration of gradient scaling beyond conventional RF limits



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8. GEOMETRY & DISTRIBUTED COUPLING

Research

Geometry Optimization and Distributed Coupling
for High Gradient NCRF Structures

Sami Tantawi



Key findings:

- Improved gradient (reduced peak fields) and RF-to-beam efficiency (higher shunt impedance) through geometry optimization and field redistribution
- Improved operational stability and reliability
- Multi-frequency designs possible (leads to shunt impedance $> 100 \text{ M}\Omega/\text{m}$)
- Compatibility with novel fabrication methods (milling in two halves, hard copper alloys, welding)



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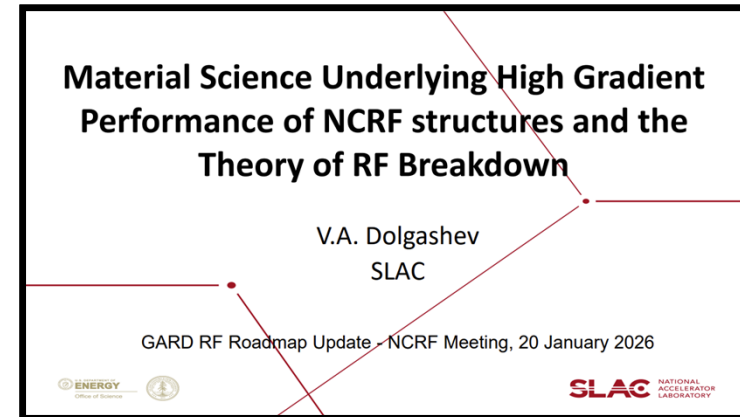
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9. MATERIALS & BREAKDOWN PHYSICS

Research

Key findings:

- RF breakdown and conditioning mechanisms remain incompletely understood. Unexplored parameter space (frequencies, pulse length, modes, temperature, magnetic field) is very large.
- There are reasons to believe that the breakdown rates are reproducible for cavities of the same material and geometry.
- Directions for experimental advances: various frequencies and multi-frequency, standing wave structures (single cell, multi cell), traveling wave structures, cryo-tests.
- Directions for theoretical advances: statistics, dislocation dynamics, molecular dynamics, macroscale PIC simulations to study damage in materials due to geometry (e.g. multipactor).



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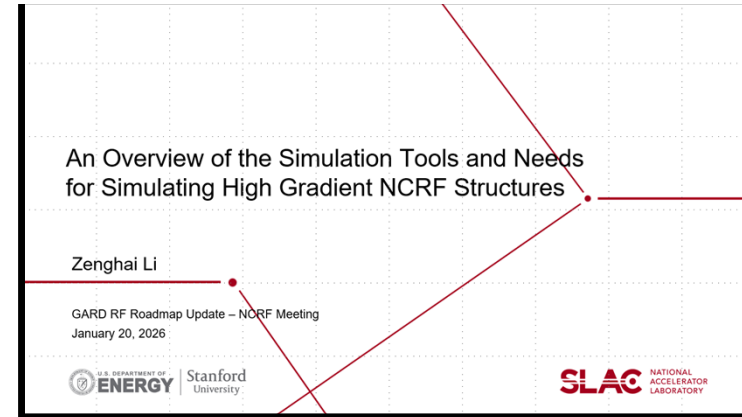
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10. SIMULATION & DIGITAL PROTOTYPING

Research



Key findings :

- Simulation capabilities evolved from design aid towards numerical prototyping (geometry fidelity, high field accuracy, multi-physics simulations).
- Large scale system analysis is possible through high power computing.
- Current needs: faster solvers, enhances scalability (large system, multi-scale geometries, wakefield computations), new physics models (breakdown and surface physics, new materials), seamless model translation (RF to mechanical to thermal to vacuum),
- Opportunities to explore: HPC and GPU-enabled computation, AI-assisted design optimization, quantum computing.



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CROSS-CUTTING RESEARCH THEMES EMERGING FROM FUNDAMENTAL TALKS

Across short-pulse, geometry, materials, and modeling research:

- Expansion of accessible parameter space beyond historical NCRF operation
- Exploration of new RF operating regimes (short pulse, cryogenic, multi-frequency)
- Shift from empirical scaling toward physics-informed breakdown understanding
- Need for predictive, multi-physics simulation capability



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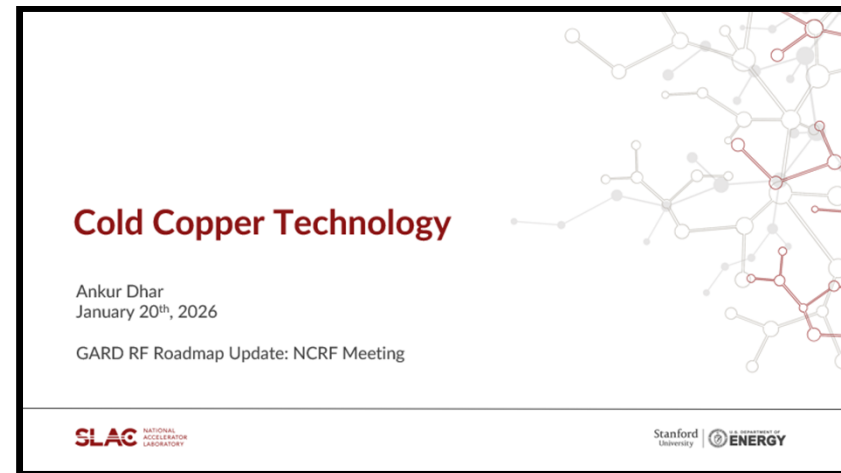
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11. COLD COPPER TECHNOLOGY (DHAR)

Development

Platform Focus:

- Cryogenic operation of normal-conducting copper / copper-alloy cavities to increase conductivity (reduce ohmic losses) and increase operational gradients
- Cryogenic operations of single cavities demonstrated in 2015 (250 MV/m). First demonstration of the full accelerating structure is 2021 (140 MV/m).
- Challenges (alignment stability, HOM damping, cryo-module design).
- Possible bigger project - Cold copper collider (C3).
- Alternative new directions: high temperature superconductors (HTS tapes)

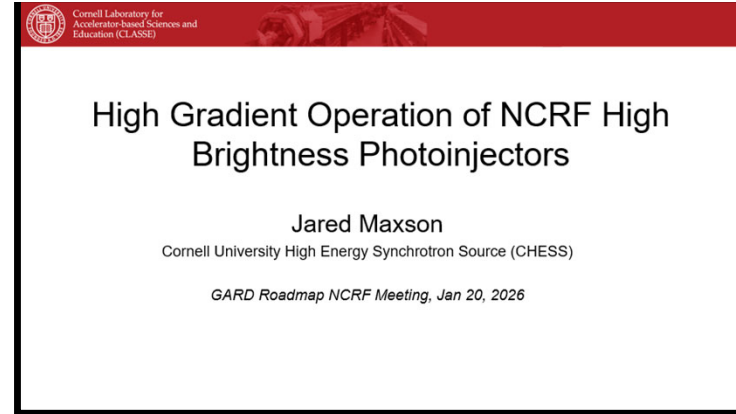


12. HIGH-GRADIENT NCRF PHOTOINJECTORS (MAXSON)

Development

Platform Focus:

- 120 MV/m gradient in a 1.6 all-copper photoinjector is demonstrated. What is next? Do we need higher gradients?
- Higher gradient allows higher charge density. But MTE also matters.
- Cryogenic NCRF injectors: increased efficiency, reduced breakdown rate, tolerable dark current at gradients as high as 300 MV/m.
- Behavior of advanced cathode materials at high gradients to be investigated (Cs_2Te , K_2CsSb , nanostructured cathodes).
- Full scale beam demonstrations needed for the new class of RF photoinjectors (cathode->gun->laser preparation-> beam dynamics correction->emittance compensation-> post accel/application).



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13. THZ & MILLIMETER-WAVE STRUCTURE-BASED ACCELERATION (POPOVIC) Development

THz and Millimeter Wave Structure Based Acceleration

Branko Popovic
GARD RF Roadmap: NCRF Meeting
01/20/26

ENERGY

RF GARD Workshop '26

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Platform Focus:

- Extension of NCRF acceleration into mm-wave and THz frequency regimes
- Possible benefits: high gradients (>1 GV/m), compactness
- Possible drive sources: two beam acceleration, gyrotrons, THz lasers.
- Issues: fabrication (machining and stacking, electroforming, CNC machining and wire EDM, 3D printing), transverse stability, attosecond-time-scale diagnostics.
- Opportunities for UED, radiation generation, and compact accelerator systems



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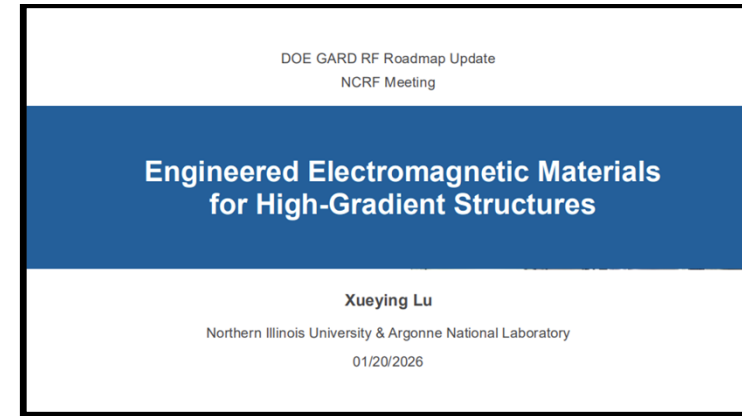
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14. ENGINEERED ELECTROMAGNETIC MATERIALS (LU)

Development



Platform Focus:

- Tailored electromagnetic structures (e.g., metamaterials, photonic bandgap concepts) to control field distributions
- Suppression or redistribution of peak electric and magnetic surface fields
- Integration of engineered EM response with cavity and waveguide geometries
- Path toward higher achievable gradients (e.g., limited RF pulse duration, breakdown insensitive acceleration regime (BIAR))
- Important research area for workforce development



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15. DIELECTRIC & NOVEL METALLIC STRUCTURES (KANAREYKIN)

Development



GARD RF Roadmap - NCRF Meeting

Dielectrics for High Gradient
Normal Conducting Structures

Alexei Kanareykin
On behalf of Euclid's/AWA ANL's team

January 20, 2026



Platform Focus:

- Simple all-dielectric geometries and metallic-dielectric disk hybrids optimized for short RF pulses and high repetition rate
- Demonstrated gradients: ~ 100 MV/m (X-band), >1 GeV/m (THz regime)
- Demonstrated shunt impedances as high as 600 M Ω /m at C-band
- Dielectric materials spanning wide permittivity range ($\epsilon_r \approx 4\text{--}50$) with low losses (loss tangent in 10^{-4} range)
- Extreme low losses at cryogenic temperatures



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DEVELOPMENT THEMES EMERGING FROM ADVANCED STRUCTURE TALKS

Across photoinjectors, THz/mm-wave, engineered architectures, dielectric platforms, and cryogenic copper:

- Pursuit of higher accelerating gradients through frequency scaling, cryogenic operation, novel materials, and architectural innovation
- Exploration of alternative cavity platforms beyond conventional room-temperature copper structures
- Integration of structure design with RF pulse format and repetition rate constraints
- Emphasis on high gradient, compactness, and high-brightness beams
- Importance for pipeline development



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OVERARCHING THEMES ACROSS 15 NCRF TALKS

Across projects, research, and development efforts, several consistent drivers emerged:

- Strong demand for lower costs (higher efficiency) and higher reliability
- Tendency towards going to higher accelerating gradients across frequency regimes
- Movement beyond conventional copper structures toward diversified platforms
- Growing need for predictive modeling, prototyping, and validation infrastructure
- Alignment between DOE mission needs and emerging compact/industrial applications



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NCRF CHALLENGE AREAS



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COMPARISON OF 2017 AND 2026

2017: 5 Specific Goals

1. Design new, simple-to-fabricate hard copper structures with integrated damping.
2. Demonstrate wakefield suppression in these novel structures.
3. Determine the impact of frequency and temperature on the high gradient limit.
4. Develop better understanding of the tradeoffs in operating frequency and temperature.
5. Demonstrate multi-frequency accelerating structures.

2026: 3-5 Challenge Areas

- **High-Gradient Operation Across Regimes.** (frequency scaling, geometry optimization, pulse length, temperature, DC magnetic field)
- **RF-to-Beam Efficiency and Linac Performance.** (shunt impedance, RF source efficiency, gradient–efficiency trade)
- **Integrated Structures with Wakefield Control.** (damping, detuning, beam loading, multi-bunch stability)
- **Materials and Manufacturing.** (cost-effective fabrication, new fabrication procedures, hard copper and copper alloys, dielectrics, metamaterials)

Cross-Cutting Enablers

- Coordinated NCRF test infrastructure & system demonstrations
- Predictive modeling & multi-physics simulation

Four technical challenges supported by two cross-cutting enablers define the 2026 NCRF roadmap.



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STRUCTURES: HIGH-GRADIENT

Challenge Area 1

Includes

Conditioning physics and statistical predictability across regimes

- Frequency scaling (L → S → C → X → THz)
- Geometry optimizations (including distributed coupling)
- RF pulse high-gradient scaling
- Temperature (Room vs Cryogenic)
- Material limitations
- Magnetic-field limits

Why it matters

- Predicts usable gradients
- Improves operational reliability
- Lowers technical risk for deployment
- Reduces conditioning time
- Expands accessible parameter space
- Enables higher usable gradient



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STRUCTURES: RF-TO-BEAM EFFICIENCY

Challenge Area 2

Includes

- Geometry optimization (shunt impedance, distributed coupling)
- Gradient–efficiency trade studies
- Long-pulse and duty-factor optimization
- System-level wall-plug → beam performance
- *RF source efficiency (klystrons, modulators, pulse compression)*

Why it matters

- Lowers operating cost
- Reduces facility power consumption
- Improves competitiveness with SRF
- Enables higher beam power at fixed infrastructure
- Supports scalable high-energy deployment



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STRUCTURES: WAKEFIELD CONTROL

Challenge Area 3

Includes

- Integrated damping and detuning
- Beam loading management
- Multi-bunch stability and wakefield suppression
- Geometry optimizations (trade-offs between shunt impedance and transverse wakefields, cell-to-cell interaction and beam stability)

Why it matters

- Enables stable acceleration of real beams
- Preserves beam quality at high gradient
- Maintains efficiency with realistic apertures
- Supports multi-bunch and high-current operation
- Transitions prototypes to application-ready structures



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MATERIALS AND MANUFACTURING

Challenge Area 4

Includes

- Base electromagnetic materials: copper, hard copper, alloys, dielectrics.
- Surface preparation & microstructure control
- Geometry optimization (cost-effective fabrication methods, reproducible manufacturing) ES1
- Engineered electromagnetic architectures (MTM, PBG, hybrid-structures)

Why it matters

- Reduced manufacturing cost
- Higher gradient
- Lower RF loss
- Faster conditioning
- Improved reliability



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ES1 I would say "breakdown modeling and development of predictive capabilities"
Evgenya Simakov, 2026-02-18T17:34:29.691

HOW THESE CHALLENGE AREAS MAP TO PROJECTS



Matrix

| | CA1 | CA2 | CA3 | CA4 |
|----------|-----|-----|-----|-----|
| FCC-ee | ✓ | ✓ | ✓ | |
| MC | ✓ | | | ✓ |
| EIC | | | ✓ | |
| BES | ✓ | ✓ | ✓ | ✓ |
| LANSCCE | ✓ | ✓ | | |
| Industry | ✓ | ✓ | ✓ | ✓ |

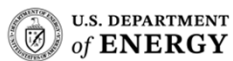
RESEARCH MILESTONES

0–3 YEARS

3–7 YEARS

7–10+ YEARS

Project milestones focus on tangible deliverables and scheduling (e.g., a software build). Research milestones focus on cognitive progress, such as validating a hypothesis or completing data collection.



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NEAR TERM (0–3 YEARS)

Near → establish & benchmark

Fabrication, Gradient, Efficiency, Stability — enabled by Modeling & Infrastructure

- 1. Establish Baseline Gradient & Breakdown Envelope Across Regimes.**
 - Define experimentally validated gradient limits vs material, frequency, pulse length, temperature, and magnetic field for base and engineered structures.[CA1, CA4]
 - 2. Establish Validated High RF-to-Beam Efficiency Approaches Across Regimes**
 - Demonstrate experimentally benchmarked RF-to-beam efficiency improvements via optimized geometry, shunt impedance enhancement, beam loading studies, and improved pulse compression concepts.[CA1, CA2, CA3]
 - 3. Design & Test Integrated High-Gradient / High-Efficiency Structure Prototypes with Beam Stability**
 - Design, fabricate, and experimentally evaluate geometry-optimized prototypes with measured wakefield control and multi-bunch beam loading behavior.[CA1, CA2, CA3]
 - 4. Standardize High-Performance Fabrication & Surface Preparation Protocols**
 - Establish reproducible manufacturing, surface finishing, conditioning, and quality control workflows applicable to high-gradient base and engineered electromagnetic structures.[CA1, CA4]
- Establish Predictive Modeling & Coordinated Test Infrastructure Baseline (Cross-Cutting)**
- Define multi-physics simulations benchmarks. Define coordinated NCRF test infrastructure for needed for integrated system validation.[Supports CA1–CA4]

CA1 → High gradient

CA2 → RF-to-beam efficiency

CA3 → Wakefield control

CA4 → Materials and manufacturing



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MID TERM (3–7 YEARS)

Mid → demonstrate & validate

Fabrication, Gradient, Efficiency, Stability — enabled by Modeling & Infrastructure

1. Demonstrate Controlled & Reproducible High-Gradient Operation Across Regimes.

- Demonstrate stable, statistically bounded breakdown performance in at least two expanded regimes (e.g., cryogenic, short-pulse, magnetic-field, dielectric-based). [CA1, CA4]

2. Demonstrate Integrated High RF-to-Beam Efficiency at Application-Relevant Scale

- Demonstrate \geq target efficiency performance in multi-cell structures with validated shunt impedance, beam loading, and pulse compression integration. [CA1, CA2, CA3]

3. Demonstrate Beam-Stable High-Gradient Structure Platforms

- Validate multi-bunch stability, wakefield suppression, and beam loading control in integrated prototypes under beam. [CA1, CA2, CA3]

4. Implement Scalable Manufacturing & Conditioning Workflows

- Demonstrate repeatable fabrication and conditioning across multiple structures with quantified cost and performance consistency. [CA1, CA4]

Validate Predictive Modeling & Infrastructure Integration (Cross-Cutting)

- Benchmark multi-physics models against expanded-regime data and deploy coordinated test facilities for regime-spanning validation. [Supports CA1–CA4]

CA1 → High gradient

CA2 → RF-to-beam efficiency

CA3 → Wakefield control

CA4 → Materials and manufacturing



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LONG TERM (7–10+ YEARS)

Long → predict, optimize, deploy

Fabrication, Gradient, Efficiency, Stability — enabled by Modeling & Infrastructure

1. Achieve Predictive, Design-Driven High-Gradient Operation Across Regimes.

- Enable reliable gradient selection based on validated models rather than empirical iteration, with quantified breakdown probability across regimes. [CA1, CA4]

ES2

2. Achieve Optimized RF-to-Beam Efficiency at System Level

- Demonstrate fully integrated linac modules achieving target efficiency with validated gradient–efficiency trade optimization. [CA1, CA2, CA3]

3. Demonstrate Application-Ready High-Gradient Structure Platforms

- Deliver beam-stable, high-gradient modules with integrated wakefield control suitable for deployment in next-generation accelerator systems. [CA1, CA2, CA3]

4. Enable Industrial-Scale Fabrication & Cost-Effective Production

- Demonstrate scalable manufacturing with defined cost-per-meter targets and reproducible high-performance conditioning outcomes. [CA1, CA4]

Establish Fully Integrated NCRF Test & Validation Ecosystem (Cross-Cutting)

- Operate coordinated facilities enabling regime-spanning validation, system-level testing, and technology transfer to projects and industry. [Supports CA1–CA4]

CA1 → High gradient

CA2 → RF-to-beam efficiency

CA3 → Wakefield control

CA4 → Materials and manufacturing



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ES1 Let's work to rephrase it together. For example, coordinated breakdown studies are definitely needed, but you forget stuff such as long pulse and alternative materials.

Evgenya Simakov, 2026-02-18T17:42:44.319

ES2 It is too ambitious to expect that this can be achieved in 3 years.

Evgenya Simakov, 2026-02-18T17:43:36.584

ALIGNMENT & BROADER IMPACT



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ALIGNMENT WITH P5 & HEP VISION

- Future colliders
- High-brightness sources
- Intensity frontier upgrades



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SYNERGY WITH OTHER DOE MISSIONS

- BES light sources
- NP facilities
- FES materials
- Medical accelerators
- National security
- Industrial compact systems



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WORKFORCE & INFRASTRUCTURE

- High-gradient test stands
- Materials science integration
- Modeling partnerships
- Industry partnerships



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END



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