General Accelerator R&D Roadmaps:
Advanced Accelerator Concepts
Radio Frequency

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HEPAP - June 5, 2017

Context: P5

- P5 Stated: "The future of particle physics depends critically on transformational accelerator R&D to *enable new capabilities* and to advance existing technologies at *lower cost*."
- P5 Recommended:
  - **"Align the present R&D program with the P5 priorities** and long-term vision, with an appropriate balance
    - among general R&D, directed R&D, and accelerator test facilities
    - and among short-, medium-, and long-term efforts"
  - **"Focus on outcomes and capabilities that will dramatically improve cost effectiveness** of mid-term and far-term accelerators."
- P5 Suggested: a HEPAP subpanel on accelerator R&D to provide detailed guidance on implementation of accelerator R&D aligned with P5 priorities.

Context: ARD Subpanel

- Following P5’s advice, DOE convened the HEPAP Accelerator R&D Subpanel.
- ARD Subpanel Executive Summary: ”The Subpanel examined the accelerator R&D that is required to prepare for the future-generation accelerators envisioned by P5.”
- **Recommendation 10. Convene the university and laboratory proponents of advanced acceleration concepts to develop R&D roadmaps with a series of milestones and common down-selection criteria.**
- The HEP Committee of Visitors has recommended that this process be applied to other components of GARD.
- Today, as “facilitator” will review roadmaps for GARD-AAC and GARD-RF.

AAC Workshop: Process

- Convened February 2-3, 2016 by DOE at this venue.
- Preceded by focused preparatory workshops.
- Proceedings very detailed and intense :
  - Presentation of individual roadmaps for PWFA, LWFA, DWFA.
  - Talks on synergies between the roadmaps and with global efforts.
  - Talks on potential early applications, diagnostic needs, simulation needs, and beam issues and challenges related to a collider.
  - Discussion of individual roadmaps with emphasis on the next 5-10 years and common challenges.
- Assumptions:
  - The primary long-term goal is a multi-TeV *e+e-* collider with a timescale set by a TDR in 2035-2040 timeframe.
  - As an intermediate goal, a TDR for a potential early application such as an XFEL or gamma-ray source.
- Workshop report at https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

AAC Workshop: Participants

- Attendees:
  - Expert proponents of LWFA, PWFA, DWFA
  - Invited accelerator science experts from universities and laboratories

- Invited participants:
  - Thomas Antonsen (Maryland)
  - Ilan Ben-Zvi (BNL, Stony Brook)
  - Jerry Blazey (NIU)
  - Yunhei Cai (SLAC)
  - Weiren Chou (FNAL)
  - Michael Downer (Texas-Austin)
  - Wei Gai (ANL)
  - Carl Schroeder (LBNL)
  - Mark Hogan (SLAC)
  - Chungguang Jing (ANL/Euclid)
  - Chan Joshi (UCLA)
  - Wim Leemans (LBNL)
  - Michael Litos (SLAC)
  - Sergei Nagaitsev (FNAL)
  - James Rosenzweig (UCLA)
  - Andrei Seryi (John Adams Inst.)
  - Bill Weng (BNL)

- Other participants:
  - L.K. Len (DOE)
  - G. Crawford (DOE)
  - E. Colby (DOE)
  - A. Lankford (HEPAP)
  - J. Siegrist (DOE)
  - J. Boger (DOE)
  - K. Marken (DOE)
  - V. Lukin (NSF)

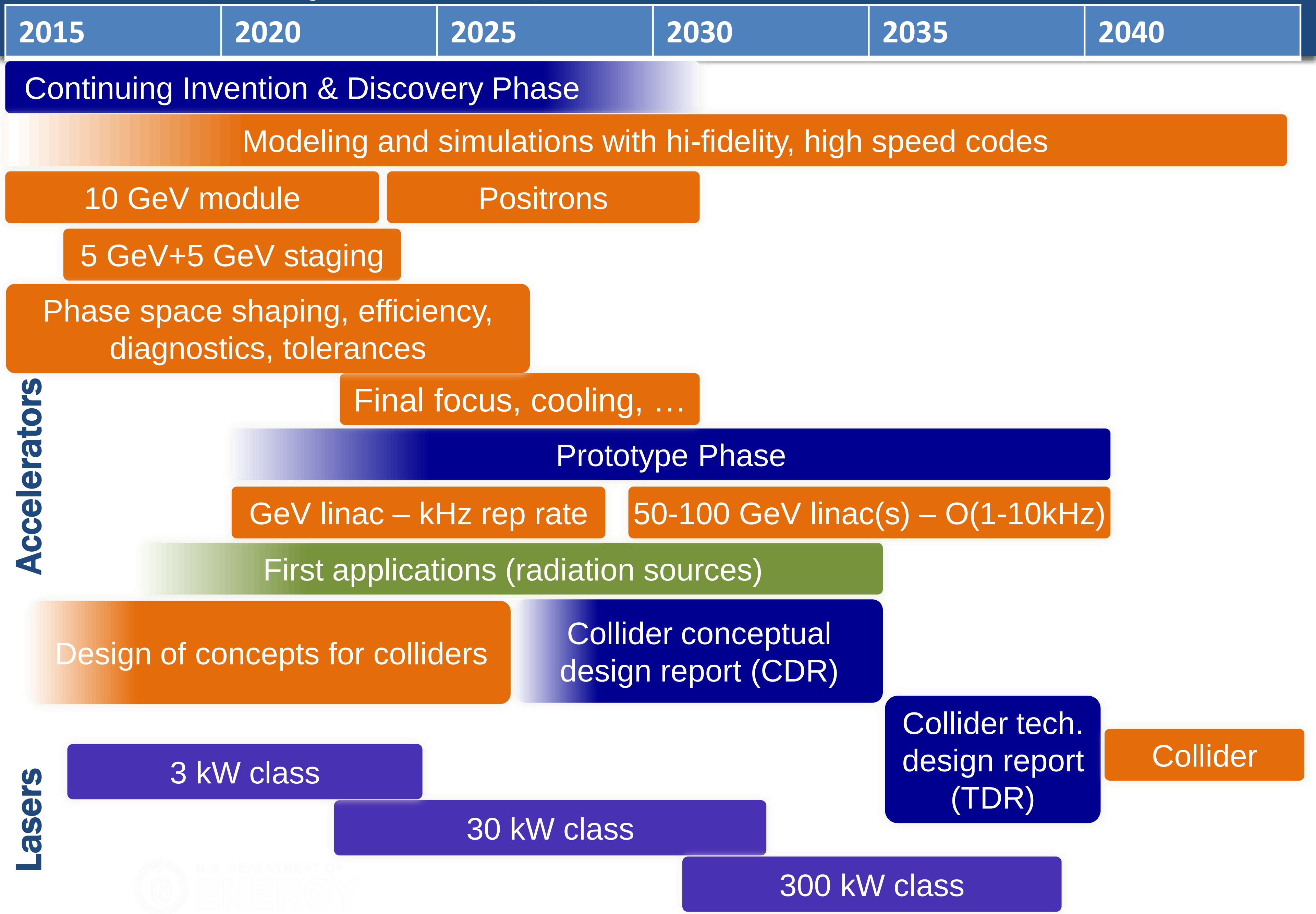
AAC Roadmap Common Challenges

- The workshop collaboratively identified a set of unifying, common challenges for the next decade:

- ***Staging:*** Higher energy* staging of electron acceleration, with independent drive beams, equal energy, and 90% beam capture.
- ***Emittance:*** Understanding mechanisms for emittance growth and developing methods for achieving emittances compatible with colliders.
- ***Higher energy electron acceleration stage:*** Completion of a single electron acceleration stage at higher energy.
- ***Positron acceleration:*** Demonstration and understanding of positron acceleration.
- ***Collider parameter set:*** Continuous, joint development of a comprehensive and realistic operational parameter set for a multi-TeV collider, to guide operating specifications for AAC.

* "Higher Energy" means multi-GeV for LWFA & PWFA and multiple 100-MeV for DWFA

Preliminary Roadmap for Laser Plasma Accelerators



LWFA: Next Decade

2016	2018	2020	2022	2024	2026

10 GeV e-beams from a single stage

Present	Goals
4.3 GeV	10 GeV
30 pC	100 pC
Unmatched guiding	Matched guiding
Fluctuates	Stable, reproducible, tunable

Second beamline on BELLA

Staging 2.0: demonstration of 5GeV+5GeV

Present	Goals
0.1 GeV boost	5 GeV
Few pC, 4% captured	100pC, >90% captured
>5 GV/m	>5GV/m
Emittance growth	Emittance preserved

Positron beams

Goal: novel concept for a compact plasma accelerator based positron source
Pair production from LPA generated e-beam
Positron beam captured in PWFA stage
Positron acceleration in laser driven stage

Laser tech R&D k-BELLA = kW class, kHz, 100 TW laser

5 Hz, 0.5-1 GeV beam

Present	Goals
ε < 0.3 micron	ε < 0.1 micron
ΔE/E ~ 1-5%	ΔE/E < 1%
Q ~10 pC	Q~10pC

γ-ray source ($>10^7$ ph/s)

LWFA powered FEL (XUV)

kHz, 0.5-1 GeV beam

Present	Goals
Limited control feedback	Full feedback stabilization
Low average power (<4 W)	High average power (>1 kW)
Pointing < 0.5 mrad	Pointing < 0.05 mrad

γ-ray source ($>10^{10}$ ph/s)

LWFA powered FEL (1-10 nm)

Plasma target and energy recovery technology

Present	Goals
Longitudinally uniform	Tapered
Parabolic	Near hollow
10 cm	>30 cm
1 kHz rep rate	10 kHz rep rate

Goals
Heat mitigation and $>10^8$ shots lifetime at kHz
Photon acceleration to reach high efficiency
Spent laser energy recovery

Diagnostics

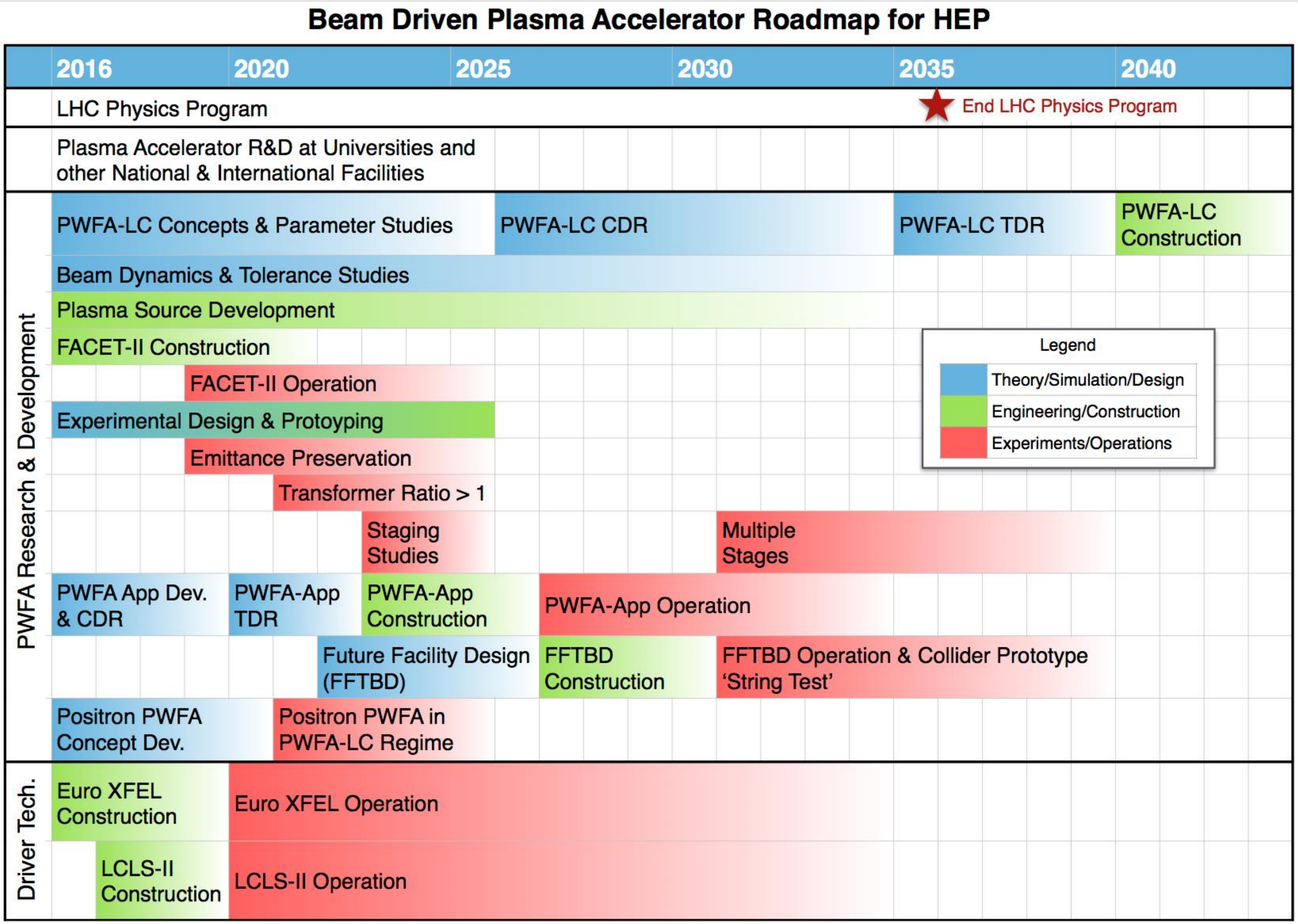
Goals
Non-invasive phase space diagnostics for 0.01-0.1-mm-mrad
Femtosecond resolution for slice properties
3-D plasma profile vs time

Simulations

Present	Goals
1 D MHD	3 D MHD
2 weeks for 1 high res 3D BELLA simulation run	<1 Hr for 1 high res 3D BELLA simulation run

- 10 GeV e-beam single stage
- 5 GeV + 5 GeV staging.
- Positron Beams
- FEL Applications
- Plasma target / energy recovery
- Diagnostics
- Simulations

Particle Wakefield Acceleration (PWFA): Roadmap Overview



- **Emittance preservation**
- **Positron acceleration**

PWFA: Next Decade

- **Throughout the 10-years:**
  - **LC concept development**
  - **Beam dynamics & tolerance studies**
  - **Early applications development**

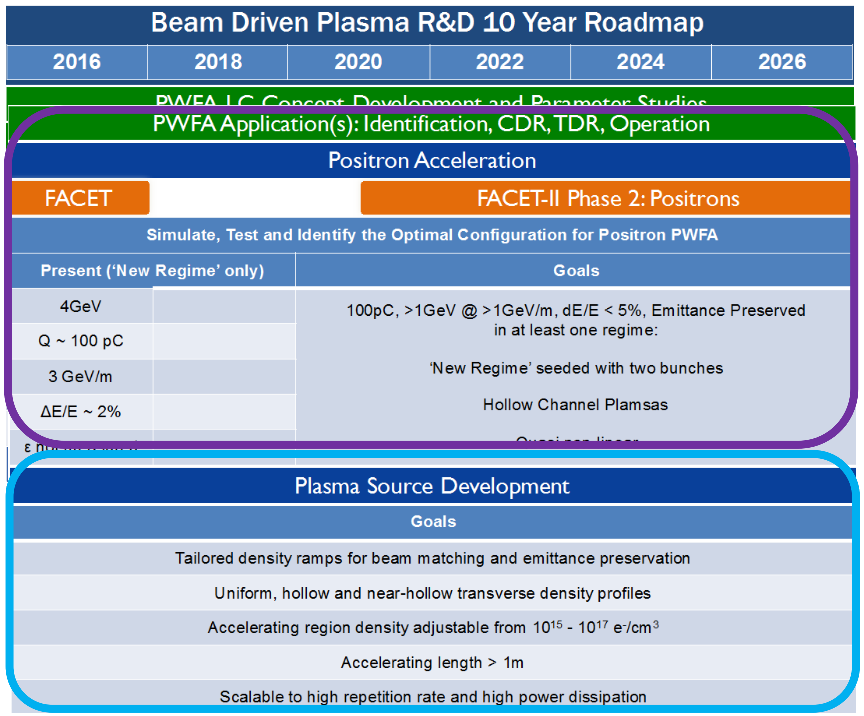
- **Program is shaped by availability of facilities.**
  - **FACET-II Phase 1 – electrons**
  - **FACET-II Phase 2 – positrons**
  - **FACET-II w/ external injector**

Beam Driven Plasma R&D 10 Year Roadmap

2016	2018	2020	2022	2024	2026
PWFA-LC Concept Development and Parameter Studies					
Beam Dynamics and Tolerance Studies					
10 GeV Electron Stage					
FACET		FACET-II Phase 1: Electrons			
Operating with high beam loading: Gradient > 1GeV/m, Efficiency > 10%					
Present		Goals			
9 GeV		10 GeV			
Q ~ 50 pC		Q ~ 100 pC			
ε ~ 100µm		ε ~ 10µm		FACET-II: External Injector	
ΔE/E ~ 4%		ΔE/E <5%		ε ~ 1µm	
Staging Studies				ΔE/E ~ 1%	
Goals				Transformer Ratio	
Characterization of active plasma lens at 10GeV				Present	Goals
Beam quality preservation during injection and extraction				Gaussian Beams	Shaped Profiles
Plasma source with tailored entrance & exit profile				T ~1	T > 1

- **10 GeV Electron Stage**
  - **FACETII will enable next step in gradient and beam quality**
  - **FACETII external injector will enable further progress (ε and ΔE)**
- **Staging Studies with independent witness beam injector**

PWFA: Next Decade



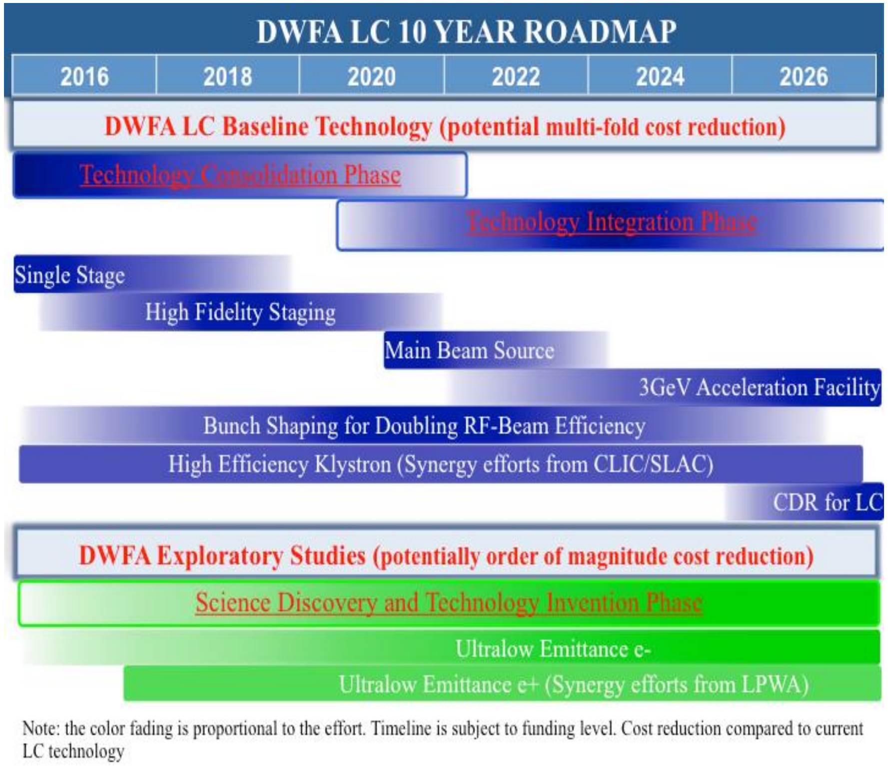
- **Positrons: FACETII Phase 2 will enable the next step in positron acceleration**
- **Plasma source development.**

Dielectric Wakefield Acceleration (DWFA): Roadmap Overview

- R&D primarily on dielectric two-beam acceleration:
  - Several critical technology elements can draw upon CLIC or ILC designs:
    - Polarized electron and positron sources
    - Beam delivery system and appropriate main-beam parameters at IP
  - The other critical technology elements are focus of current R&D:
    - Main (witness) beam acceleration
    - Drive beam power source
    - Staging of multiple accelerations structures to higher energy

- Goals:
  - 300 MV/m gradient
  - Low-cost dielectric structures
  - Simple drive-beam based power source
  - Main bunch shaping for high efficiency
  - High-efficiency klystrons
  - Multi-fold cost reduction compared to current LC technology

DWFA: Next Decade



- 2016-21 – Technology Consolidation Phase
  - Single stage
    - GW level RF power from drive beam
    - 300 MV/m in single stage
  - High Fidelity Staging
    - With beam kicker, RF delay lines, two TBA modules per stage
- 2021-26 – Technology Integration Phase
  - Main Beam Source
    - X-band
  - 3-GeV Acceleration Facility
    - High-fidelity, integrated test facility
    - High-gradient
    - Staging
    - LC quality beam
- Ongoing:
  - Bunch Shaping
    - Increase RF-beam efficiency
  - High Efficiency Klystron
    - Synergistic with CLIC (and SLAC)

AAC Synergies

- Many similarities and parallels in LWFA & PWFA roadmap, considerable physics and required R&D are independent of the driver.
  - Staging of 1-10 GeV modules
  - Mitigation of emittance growth due to collisions and ion motion
  - High-efficiency acceleration
  - Positron acceleration
  - Hollow plasma channels for positrons
  - Mitigation of transverse beam instabilities

- Similar timescales for progress

- Use of BELLA, FACET-II, ATF, and AWA as appropriate to each study will foster progress.
    - E.g.: positrons studies at FACET-II; staging and tolerances at BELLA; first studies of plasma lenses at ATF, moving to BELLA & FACET-II for higher energies; AWA for staging and bunch shaping.

- Synergies of DWFA with CLIC

RF Workshop: Process

- Convened February 8-9, 2017 in Gaithersburg, MD.
- Preceded by focused preparatory workshops and SLAC and FNAL.
- Proceedings (also detailed, intense discussions):
  - Presentation of preparatory workshops & preliminary roadmaps for both SRF and NCRF.
  - Detailed talks on the status of modeling, international efforts, potential NCRF/SRF synergies beyond HEP, laboratory needs, university roles, user needs, and test facilities at SLAC and FNAL.
  - Discussion of cross-cuts
  - Review and integration of the two roadmaps
- Overarching themes:
  - Dramatically improve performance and cost by an order of magnitude or more.
  - Decadal time scale for the roadmap informs improved performance and cost of accelerators now under consideration.
- Currently discussing a mature draft which forms the basis of this talk.

RF Workshop: Participants

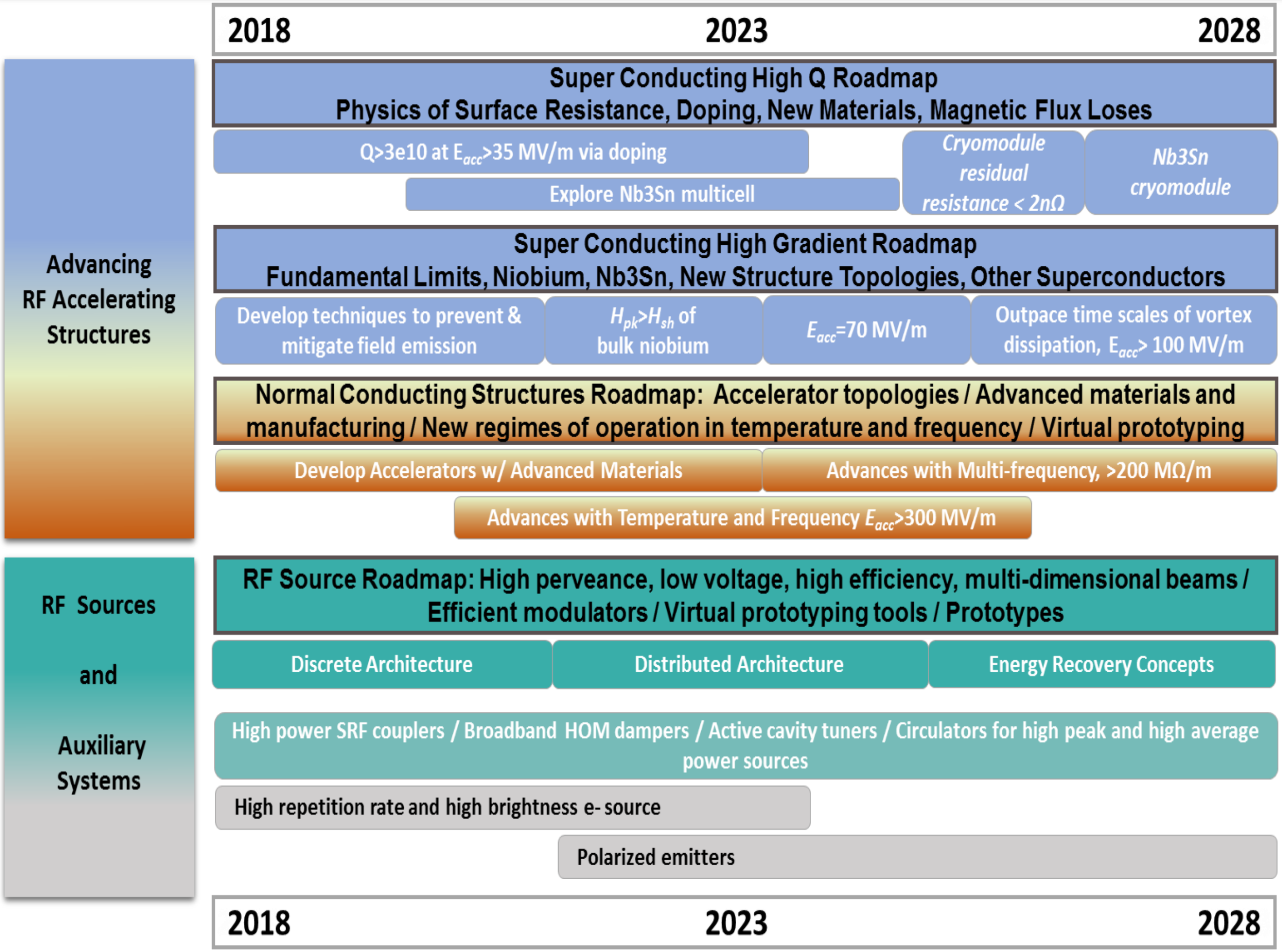
- Attendees:
  - Experts on SRF, NCRF, RF sources, and auxiliary RF systems
  - Invited accelerator science experts from universities and laboratories

- Invited participants:
  - Sami Tantawi (SLAC)
  - Seregy Belomestnykh (FNAL)
  - Cho Ng (SLAC)
  - Jerry Blazey (NIU)
  - Erk Jensen (CERN)
  - Richard Temkin (MIT)
  - Weiren Chou (FNAL)
  - Bruce Carlsten (LANL)
  - Wim Leemans (LBNL)
  - Emilio Nani (SLAC)
  - Anna Grassellino (FNAL)
  - Mathias Liepe (Cornell)
  - Alex Gurevich (Old Dominion)
  - Robert Rimmer (Jefferson)
  - James Rosenzweig (UCLA)
  - Sergei Nagaitsev (FNAL)
  - Lia Merminga (SLAC)

- Other participants:
  - L.K. Len (DOE)
  - G. Crawford (DOE)
  - E. Colby (DOE)
  - V. Lukin (NSF)
  - J. Siegrist (DOE)
  - J. Boger (DOE)
  - A. Lankford (HEPAP)

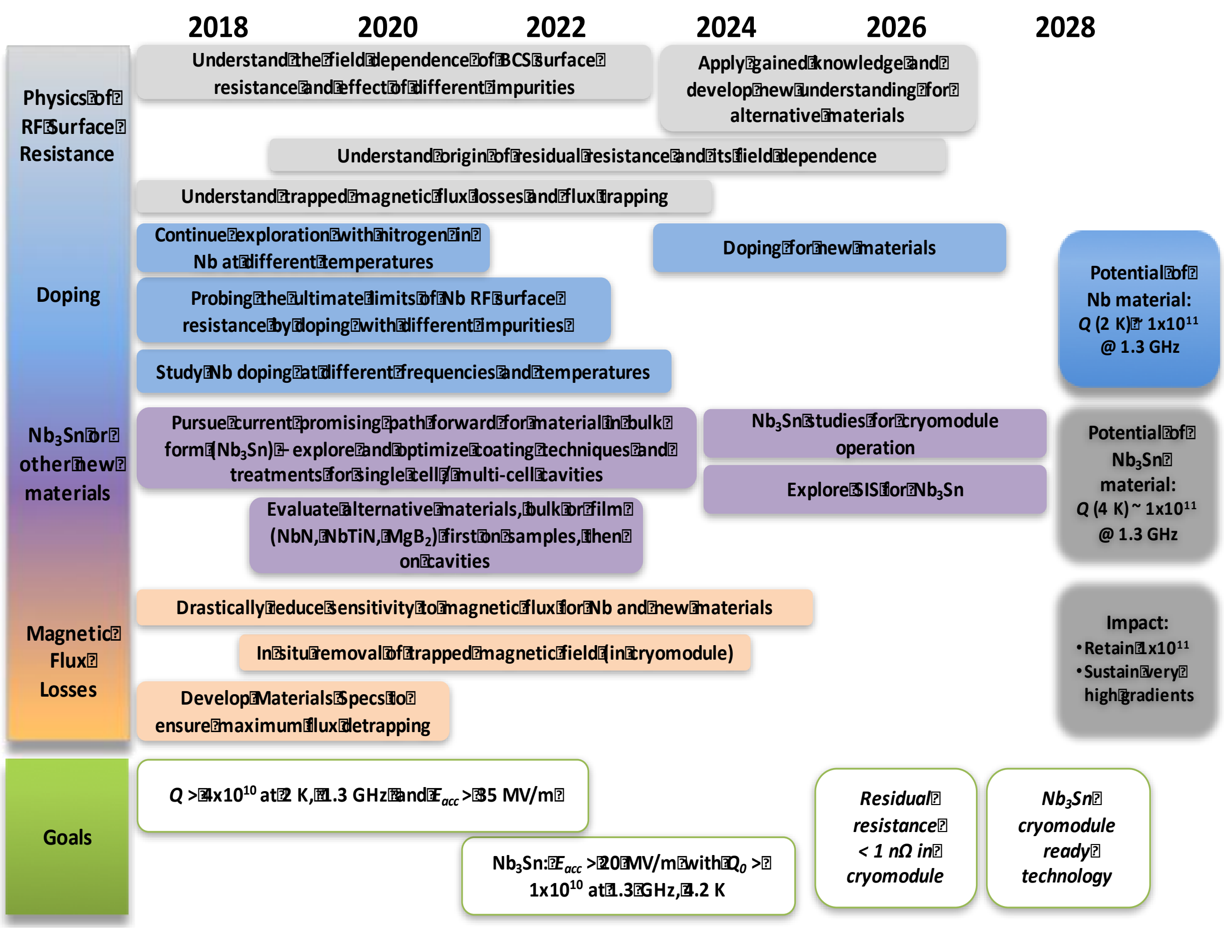
(Apologies to anyone missed!)

Integrated Roadmap



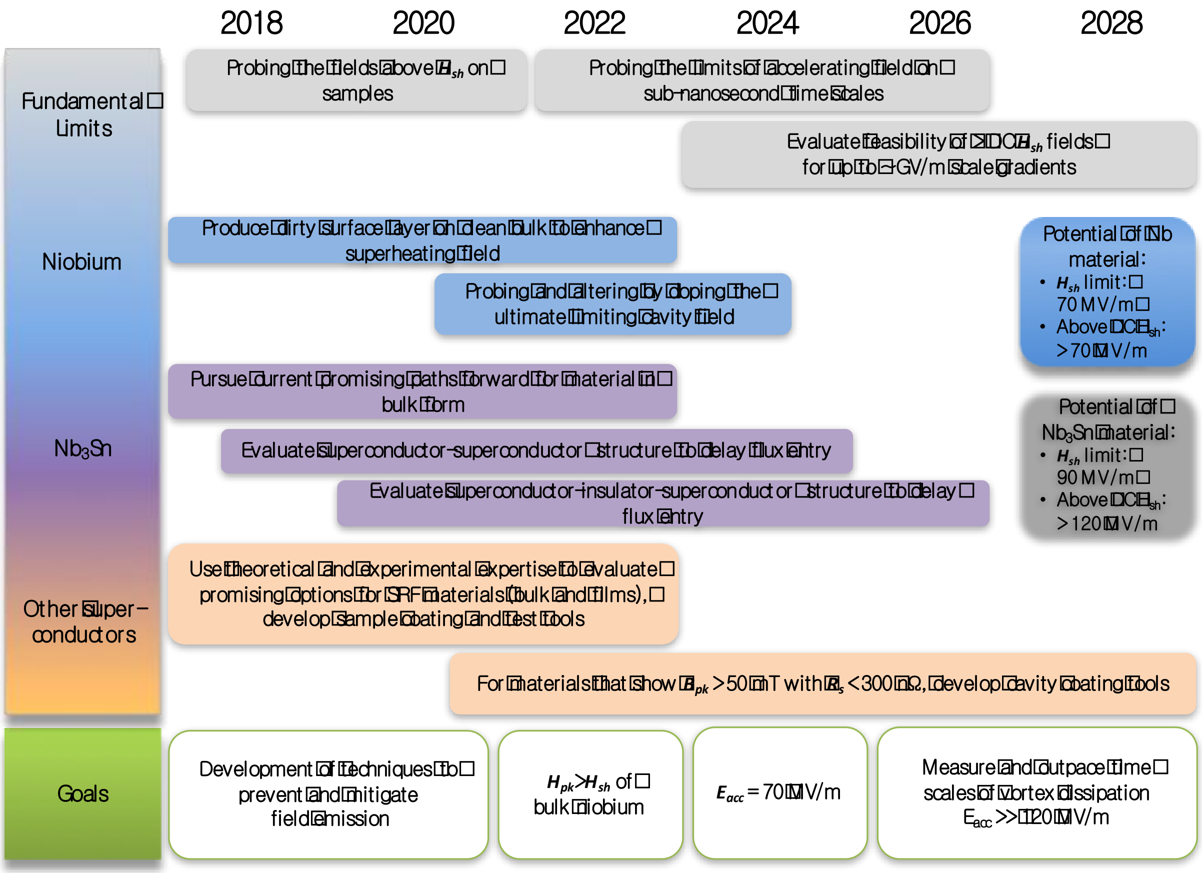
- Decadal integrated roadmap
- Two main components
  - RF structures
  - RF sources & auxiliary systems
- Themes or cross-cuts for cryogenic or warm RF structure R&D:
  - Understanding basic physics and processes
  - Exploring new shapes, materials, and operating regimes.

SRF: High Q



- Investigate the physics of RF surface resistance
- Explore doping
- Examine new materials
- Physics of magnetic flux losses

SRF: High Gradient



- Fundamental limits
- Niobium surface treatment and doping
- New materials

NCRF: New Structures

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%

- Advanced topologies, materials and manufacturing.
- New temperature and frequency operating regimes.

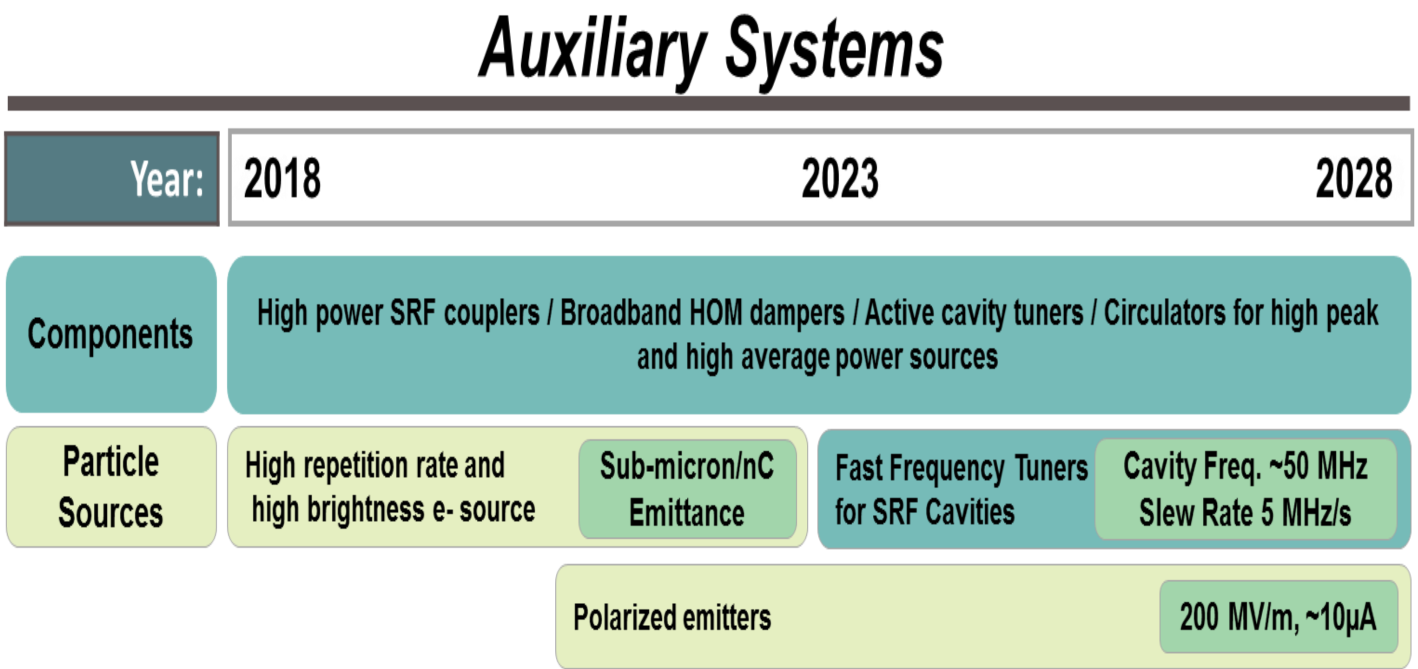
RF Sources

RF Source Roadmap

Year:	2018	2023	2028
RF Sources	High perveance, low voltage, high efficiency, multi-dimensional beams / Efficient modulators / Virtual prototyping tools / Prototypes / Energy recovery		
	Discrete Architecture	Distributed Architecture	Energy Recovery Concepts
Pulsed Sources Projected Cost Power Delivery Efficiency	Prototype Sources 20 $/kW Peak Pulsed 65 MW/m 35%	Integrate with Accelerators 5 $/kW Peak Pulsed 100 MW/m >50%	Technology Transfer 2 $/kW Peak Pulsed 200 MW/m >70%
CW Sources Projected Cost Power Delivery Efficiency	CW sources 650 MHz / 1.3 GHz 5 $/W Avg. CW 100 W >50%	Cost-Effective CW Sources 2 $/W Avg. CW 100 Kw >70%	CW Sources at Facilities <1 $/W Avg. CW 100 kW >80%

Explore discrete architectures (multi beam klystron) , distributed architectures (radial klystron), and energy recovery concepts to reach high perveance while operating at lower voltage and higher efficiency.

RF: Auxiliary Systems



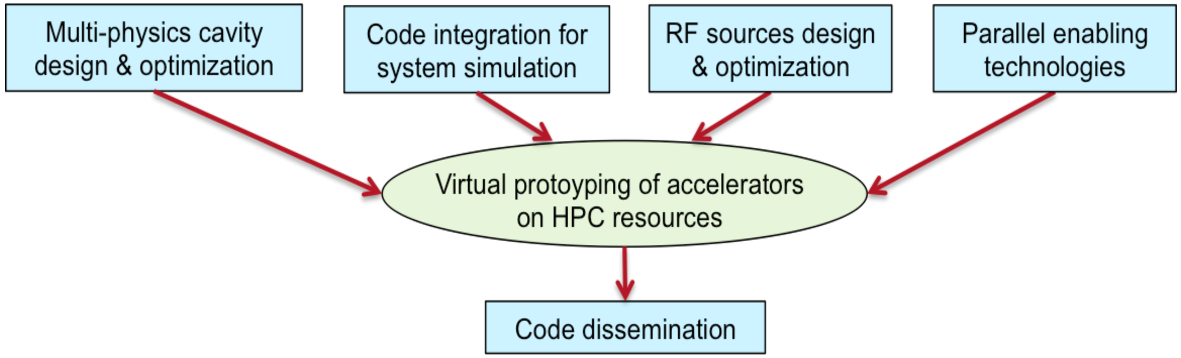
- Electron sources
- Higher Order Mode damping
- Power couplers
- Fast frequency tuners for SRF cavities
- Rapidly tunable NCRF cavities.

RF Synergies

- SRF/NCRF synergies
  - Surface physics of the cavity
  - Novel fabrication methods
- Office of Science synergies
  - Nuclear physics (ATLAS, RHIC, FRIB)
  - Spallation sources (SNS, ESS)
  - Light sources (LCLS-II, NSLS-II, XFEL…)
- Federal Sponsors & Industry
  - Interrogation
  - Medicine
  - Reinvigorating commercial RF sector

As seen by AAC and RF: GARD Computational Needs

- A strong modeling program is a critical component of R&D progress.
- Requirements:
  - Development of personnel and of computational teams
  - Development of new multi-scale models and algorithms



  - Exploitation of new processor architectures
- Addressing these requirement is itself a challenge.

Closing Comments

- The Advanced Accelerator Concepts and Radio Frequency communities invested significant time and effort to develop integrated, comprehensive, and detailed roadmaps.
- Roadmaps responsive to
  - P5 request for alignment of R&D with priorities and improved cost and operation.
  - ARD request for detailed milestones and goals.
- AAC roadmap identifies and addresses five common challenges for LWFA, PWFA, DWFA: a higher energy stage, emittance control, acceleration stages, positron acceleration, maintenance of a collider parameter set.
- RF roadmap addresses performance and cost goals through a focus on SRF and NCRF accelerating structures and RF and auxiliary systems.

(For details consult your local accelerator experts)

ARD GARD-AAC Recommendations

- **Recommendation 7.** Vigorously pursue particle-driven plasma wakefield acceleration of positrons at FACET in the time remaining for the operation of the facility. Be-tween the closing of FACET and the operation of a follow-on facility, preserve the momentum of particle-driven wakefield acceleration research using other facilities.
- **Recommendation 8.** Continue to support laser-driven plasma wakefield acceleration experiments on BELLA at the current level.
- **Recommendation 9.** Reduce funding for direct laser acceleration research activities.
- **Recommendation 10.** Convene the university and laboratory proponents of advanced acceleration concepts to develop R&D roadmaps with a series of milestones and common down-selection criteria

ARD GARD-RF Recommendations

- **Recommendation 4.** Direct appropriate investment in superconducting RF R&D in order to inform the selection of the acceleration technology for the multi-MW proton beam at Fermilab.
- **Recommendation 6.** Increase funding for development of superconducting RF (SRF) technology with the goal to significantly reduce the cost of a ~1 TeV energy upgrade of the ILC. Strive to achieve 80 MV/m accelerating gradients with new SRF materials on the 10-year timescale.
- **Recommendation 11.** Continue research on high-efficiency power sources and high-gradient normal conducting RF structures.
- **Recommendation 12.** Make NLCTA available for RF structure tests using its RF power and beam sources.
- **Recommendation 13**. Focus normal conducting RF R&D on developing a multistage prototype based on high-gradient normal conducting RF structures and high-efficiency RF power sources to demonstrate the effectiveness of the technology for a multi-TeV *e+e-* collider.

LWFA: Decadal Laser Roadmap

2016	2018	2020	2022	2024	2026

k-BELLA: kW class, kHz, 100 TW laser

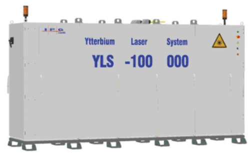
"Stepping stone": 30 kW class

Fiber Laser Technology

▲ 100mJ/30fs/kW & contrast demo

~1J & contrast demo ▲

Present	Goals: near term	Goals: mid term
1-5mJ	100mJ – >1J	30J
~500W	3kW	30kW
~300fs	~30fs	~100fs
Contrast: 10 - 20dB	Contrast 30 - >40dB	Contrast 50 - >60dB

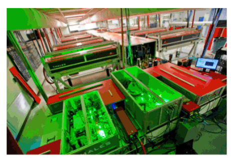


Ti:sapphire

▲ Scaling to 3kW demo

~80% WPE pump laser & power scaling demo ▲

Present	Goals
1-10Hz	1kHz
WPE: << 5 %	WPE: >15%
< 100W	>3kW



k-BELLA: kW class, kHz, 100 TW laser

"Stepping stone": 30 kW class

Common Technologies

▲ Ready for 30kW class laser demo

Goals		
>30kW mirrors and coatings	>30kW and broadband beam combiners	Contrast enhancing technology (e.g. plasma mirrors) operating at >1kHz
>30kW pulse compression gratings	>30kW adaptive optics	

Direct-CPA bulk

Goal: suitable diode-pumped solid-state material meeting pulse duration, energy, average power, and WPE requirement simultaneously

CO_2

100fs with ~25% WPE demo ▲

Goals: increase efficiency and reduce pulse duration simultaneously, increase system reliability and meet size requirements
100fs with >25% WPE

OPCPA

- Laser R&D cannot be overlooked, technological progress essential
- 30kW, kHz class laser represents an appropriate next step.

LWFA Update

- **Modeling and simulations**: novel algorithms resulting in higher speed modeling codes, EXASCALE project funded for developing tools to carry out start-to-end modeling of a 1 TeV laser plasma based colliders
- **10 GeV module**: experimental demonstration of dynamic shaping of plasma channels in capillary discharges with laser heater pulse to provide guiding of high intensity laser pulses at lower plasma densities than previously achieved. Designed, built and operated 20 cm long monolithic capillary discharges, another key step towards higher energies. Experiments underway at BELLA towards 10 GeV with these significant new developments and preliminary results are very promising.
- **Staging**: two independently powered modules at 100 MeV per stage were demonstrated) and a design for staging at 5 GeV+5GeV was completed. FWP submitted to DOE for second beamline on BELLA to enable experiment.
- **Phase space shaping, efficiency, diagnostics, tolerances**: demonstrated a reliable, tunable injector based on gas jet with knife blade first emittance measurement of two different injection techniques
- **Design of concepts for colliders**: studied impact of ion motion in plasmas for ultra-intense electron beams; analyzed beam-breakup (BBU) instability and found new method for stabilization BBU was seen as a potential roadblock but a viable solution has emerged.
- **Applications**: two new lasers (100 TW class) and beamlines under construction towards a laser plasma accelerator driven XUV free electron laser and a tunable gamma ray source
- **High average power demonstrator (k-BELLA):** organized workshop with national and international experts and solid approach(es) have been identified for the near future 3 kW system as well as for future 10's to 100's of kW average power collider class lasers with high wallplug efficiency.

PWFA Update

- FACET successfully finished its final run in April 2016 & published several key new results:
  - Investigated head-erosion mechanism mitigation to enhance energy extraction from drive bunch
  - Demonstrated a Positron Beam-Driven Hollow Channel Plasma Wakefield Accelerator
  - Mapped the longitudinal field structure within non-linear plasma wake to inform emittance preservation studies
  - Demonstrated record performance (gradient, energy gain, efficiency) for dielectric wakefield accelerators

- Data analysis and high-impact publications in preparation or out for review on:
  - Laser-triggered injection in electron-beam driven plasma wakefield accelerators - important for studying emittance preservation and developing first off-ramp applications
  - Acceleration of a trailing positron bunch in a plasma wakefield accelerator - first measurements of positron acceleration spanning non-linear to quasi-linear regimes to identify optimum regime for positron PWFA and LWFA

- Planning for FACET-II as a community resource with 3rd annual science workshop in October 2017

DWFA Update

- Single stage
  - 11.7 GHz Metallic structure
    - (Gradient continues to increase over last year)
    - 300 MW RF (drive beam power generation
    - 150 MV/m (main beam acceleration)
  - 26 GHz Dielectric structure
    - (TBA demonstrated for first time in 26GHz dielectric)
    - 300 MW RF (drive beam power generation
    - 150 MV/m (main beam acceleration)

- High Fidelity Staging
  - Fast kicker:
    - design completed,
    - in fabrication,
  - RF delay lines:
    - under construction,
  - Two TBA modules for both stages
  - Structures:
    - in-hand
  - Staging Beamline:
    - under design
- AWA User Facility Program
    - Adding many user's: (e.g. UCLA PWFA, US-Japan FNAL/NIU, etc.)

DWFA: Applications

DWFA OTHER APPLICATIONS and SYNERGIES

2016	2018	2020	2022	2024	2026

Other Applications

MHz Rep. Rate DWA-XFEL (collaboration w/ APS)

Present	Goals
Conceptual design done	Testing critical technology elements in the fabrication process
End to end beam simulation done	Finishing a meter scale module
Engineering design started	PoP beam experiment

CDR/TDR

Goals
Ready for CDR /TDR

High Brightness Electron Source (collaboration w/ MaRIE)

Goals
Characterizing Ultrahigh brighness electron gun for MaRie Project

Synergies for PWFA/LWFA

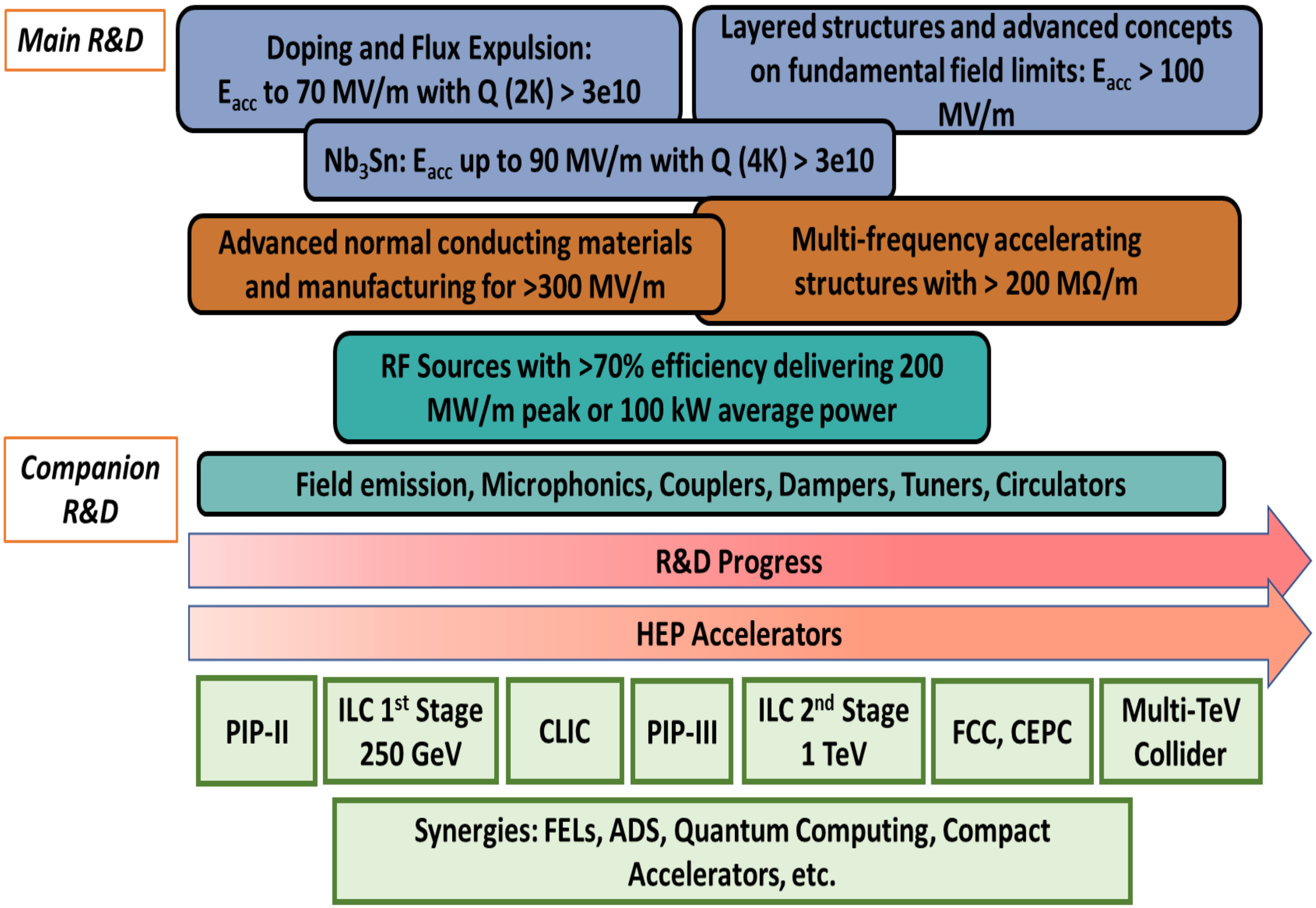
PWFA Staging

Goals
Demo of the1st staging for PWFA

High Transformer Ratio for PWFA/LWFA

Goals
Demo of Transformer ratio>2

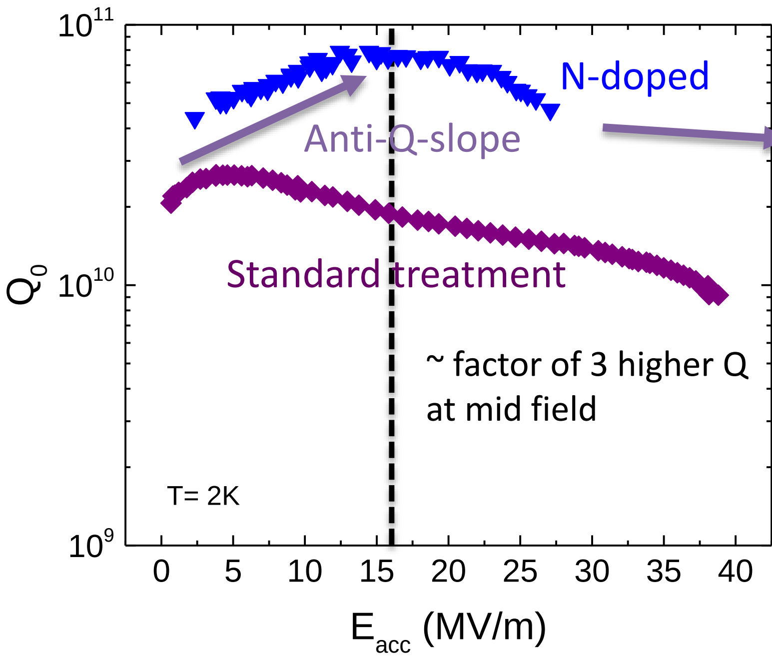
Alignment with Future Accelerators



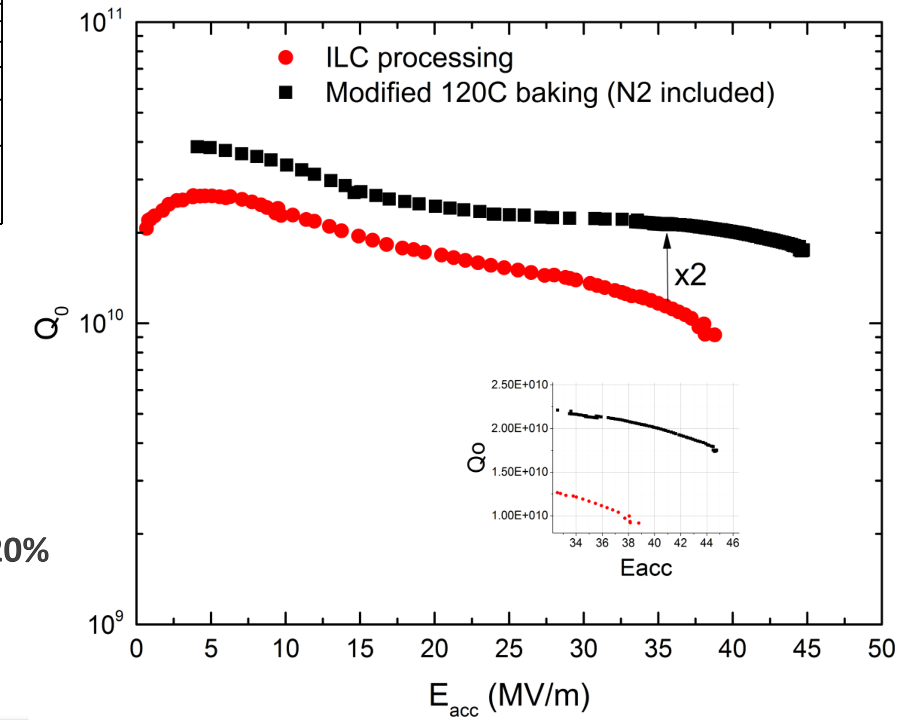
SRF Common Roadmap Elements

- New Materials, Films, and Multilayers:
- Development of Nb_3Sn as Practical SRF Material
- Field Emission Mitigation
- Microphonics and Lorentz Force Detuning Compensation
- Novel SRF Cavity Shapes

High Q/Gradient Start of the Art

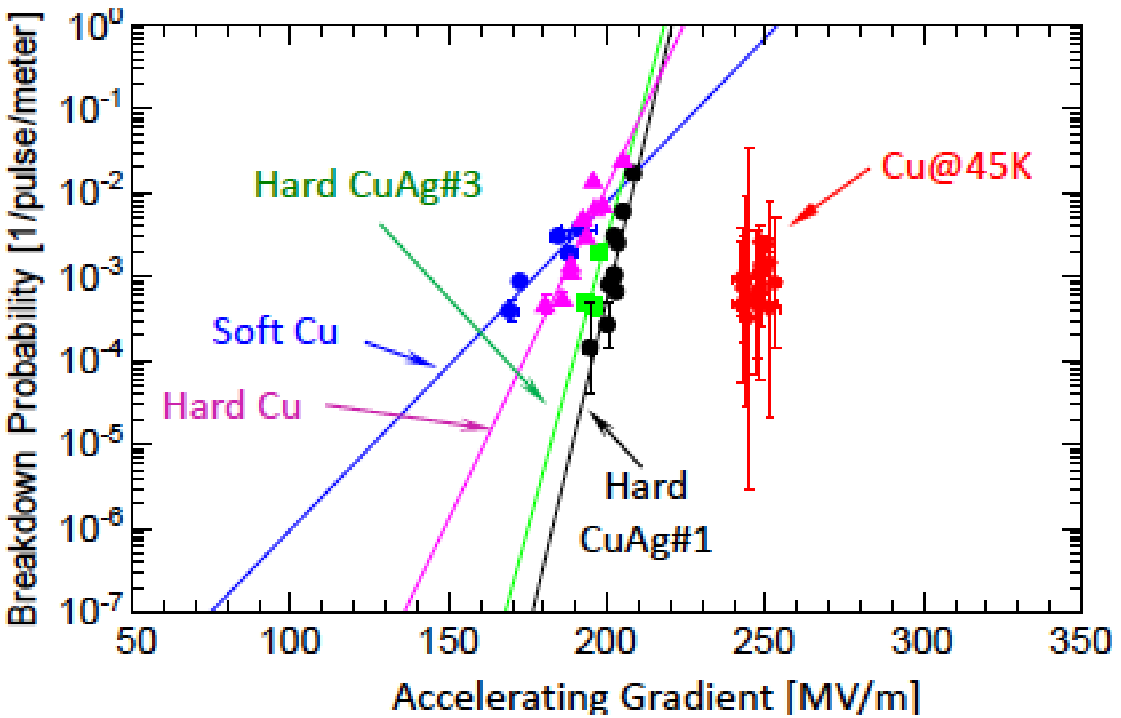


Anti-Q-slope emerges from the BCS surface resistance <u>decreasing</u> with field



Increase in Q factor of two, increase in gradient ~20% (only single-cell cavities to date)

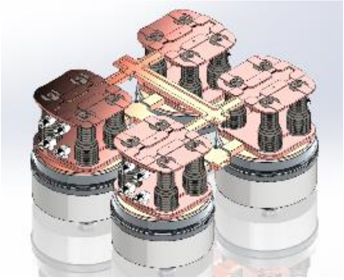
Progress on NCRF Gradients



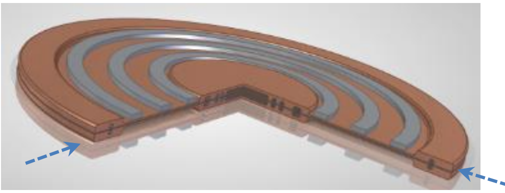
Advance RF Source Concepts/Low Cost & Low Voltage

- **Discrete Architecture:**
  - **Modular-Array Multi-Beam Klystron**
    - Redefining the landscape of multi-beam architectures.
      - Simplified, low part count, klystrinos
      - Phase locked Floquet power extraction network
- **Distributed Architecture:**
  - **Radial Klystron**
    - Exploiting a novel geometry to mitigate space charge effects.
      - Low space charge radially propagating beam
  - **Deflected Beam Amplifier**
    - Multi-stage power extraction that enables high efficiency X-band operation.
      - Complete beam-wave synchronism with multi-stage output structure.

Multi-beam klystron



Radial klystron



Deflected beam amplifier

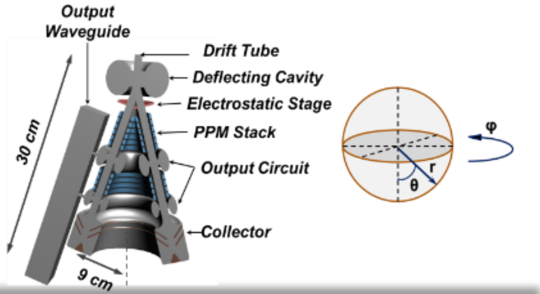


Table 1. Milestones for RF modeling and simulation R&D thrusts.

Year	Milestone
1 - 2	Time domain thermal and mechanical solvers for cavity design; Integration of RF and beam dynamics codes for emittance calculation; Solver components for 2D modeling of RF sources; Nonlinear eigensolvers for damping calculation; GUI for multi-physics cavity design.
3 - 4	Capability for EM mode damping calculation for all boundary conditions; Integration of RF and radiation codes as a coupled system; 2D large-signal code for RF source design; Parallel RF shape optimization tool; GUI including RF shape optimization tool
5 – 6	Coupled time domain thermal and mechanical solver for cavity design; System-level integrated RF and beam dynamics simulation; Tool for analysis of spurious oscillations in RF sources; Nonlinear eigensolvers for dispersive lossy materials; GUI for code integration
7 – 8	Capability for microphonics simulation in cryomodule systems; System-level integrated RF and radiation calculation; 3D large-signal code for RF source design; Parallel multi-physics shape optimization tool; Dissemination of RF source codes
9 - 10	Multi-physics shape optimization of large accelerator systems; End-to-end integrated simulation; Optimization procedures for RF source codes; Performance enhancement of parallel codes on emerging supercomputing platforms; GUI for multi-physics shape optimization tool