Developments in SRF Technology for Light Source Applications

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Workshop on Future Light Sources
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SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

The name of the game is Q_0

High Repetition Rate
(1 MHz for LCLS-II & SHINE)

→ **CW Cavity Operation**

↓ **Optimize Cryogenic Losses**
(Low P_{diss} means smaller cryoplants)

← **High Q_0**

↘ **Maximize Achievable Beam Energy**

Outline

Achieving High Q_0 in SRF Accelerators

LCLS-II-HE at SLAC

SRF Developments at Fermilab

SRF Activities and Plans at DESY

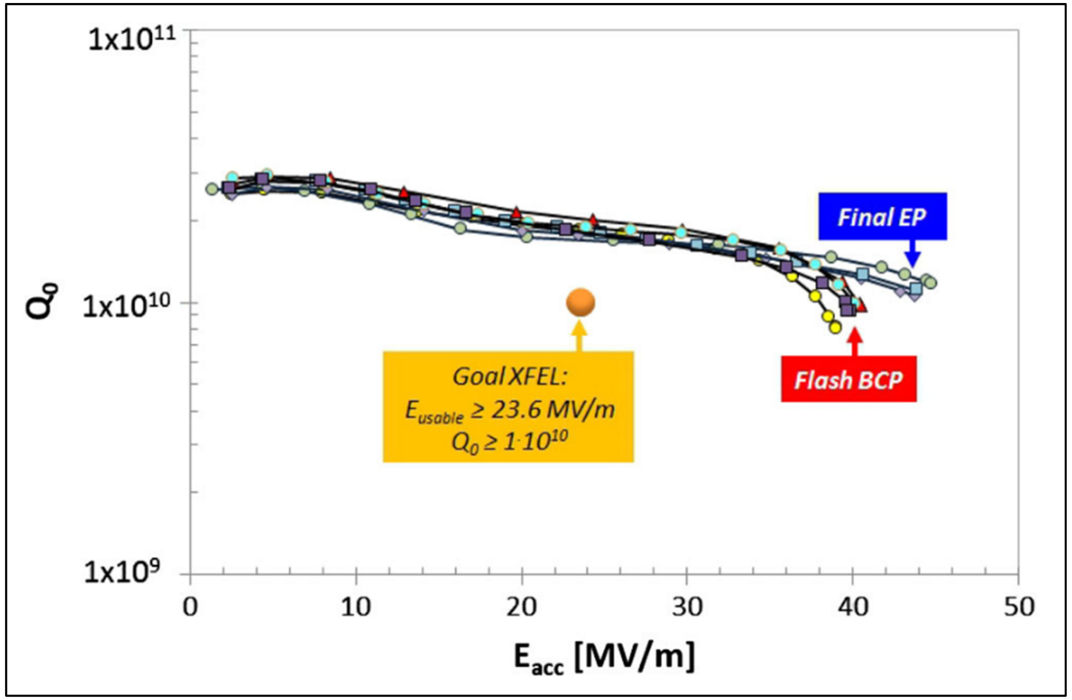
Summary & Outlook

Achieving High Q_0 in SRF Accelerators

Developments in SRF Technology

2010

EU-XFEL Cavity Construction



W. Singer et. al.

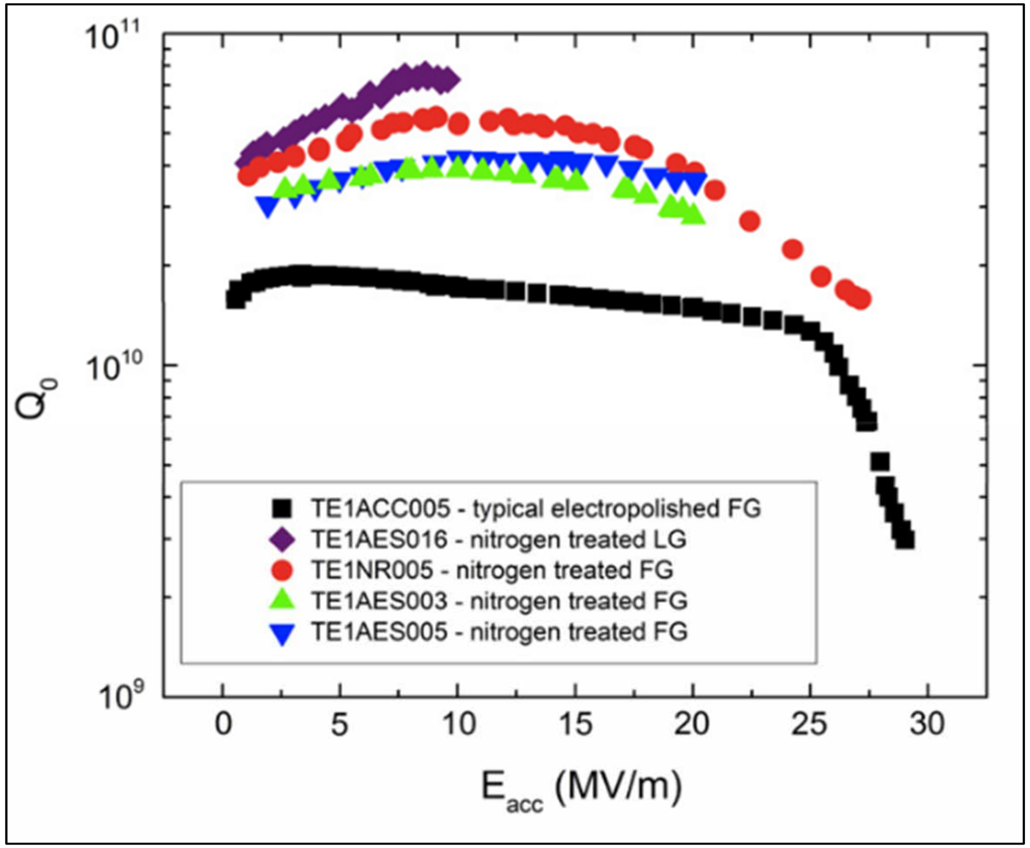
Developments in SRF Technology

2010

EU-XFEL Cavity Construction

2013

Discovery of N-Doping



A. Grasselino et. al.

Developments in SRF Technology

2010

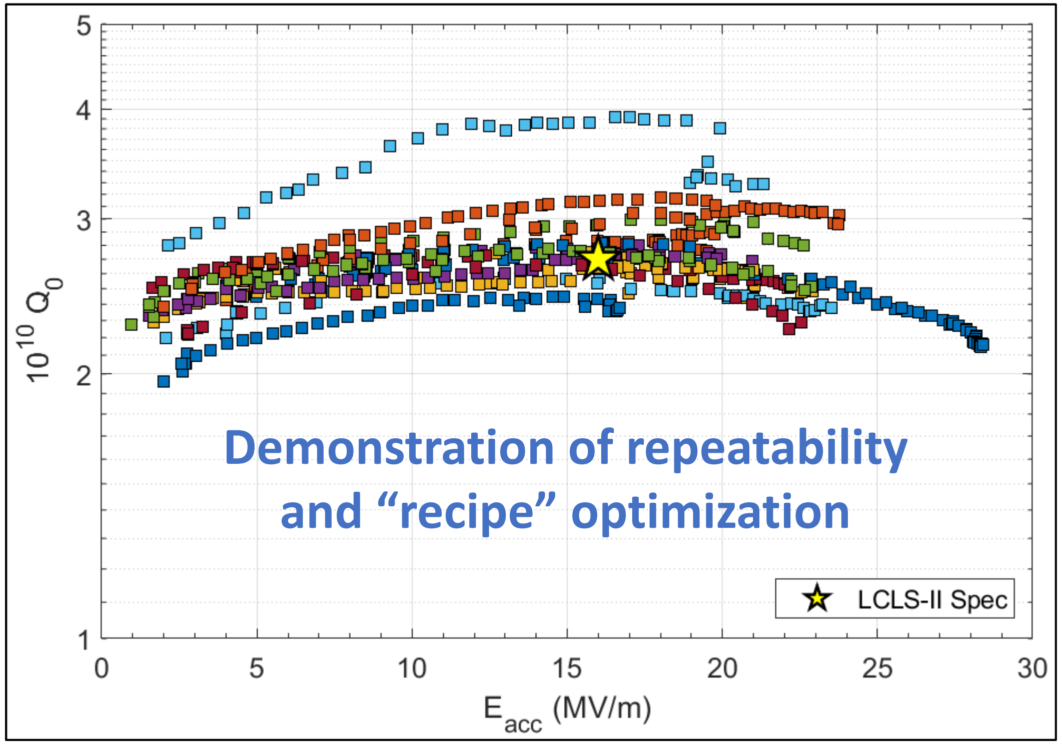
EU-XFEL Cavity Construction

2013

Discovery of N-Doping

2014-2016

LCLS-II High Q_0 R&D



Demonstration of repeatability and "recipe" optimization

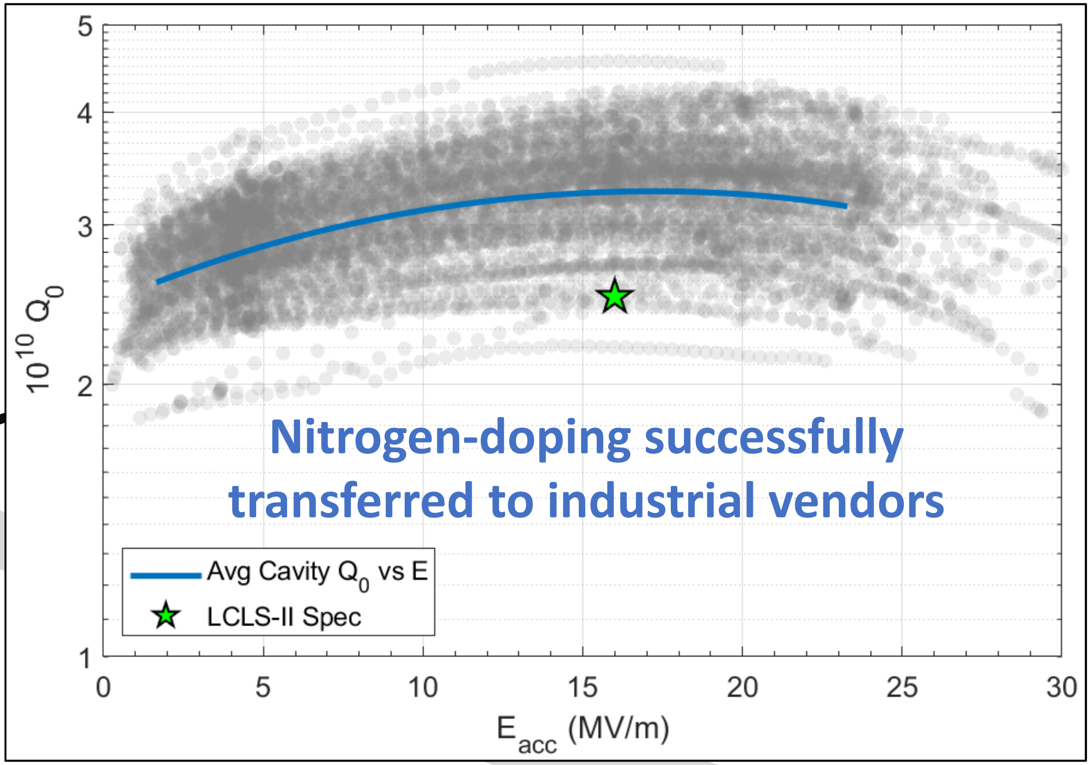
Developments in SRF Technology

2010
EU-XFEL Cavity Construction

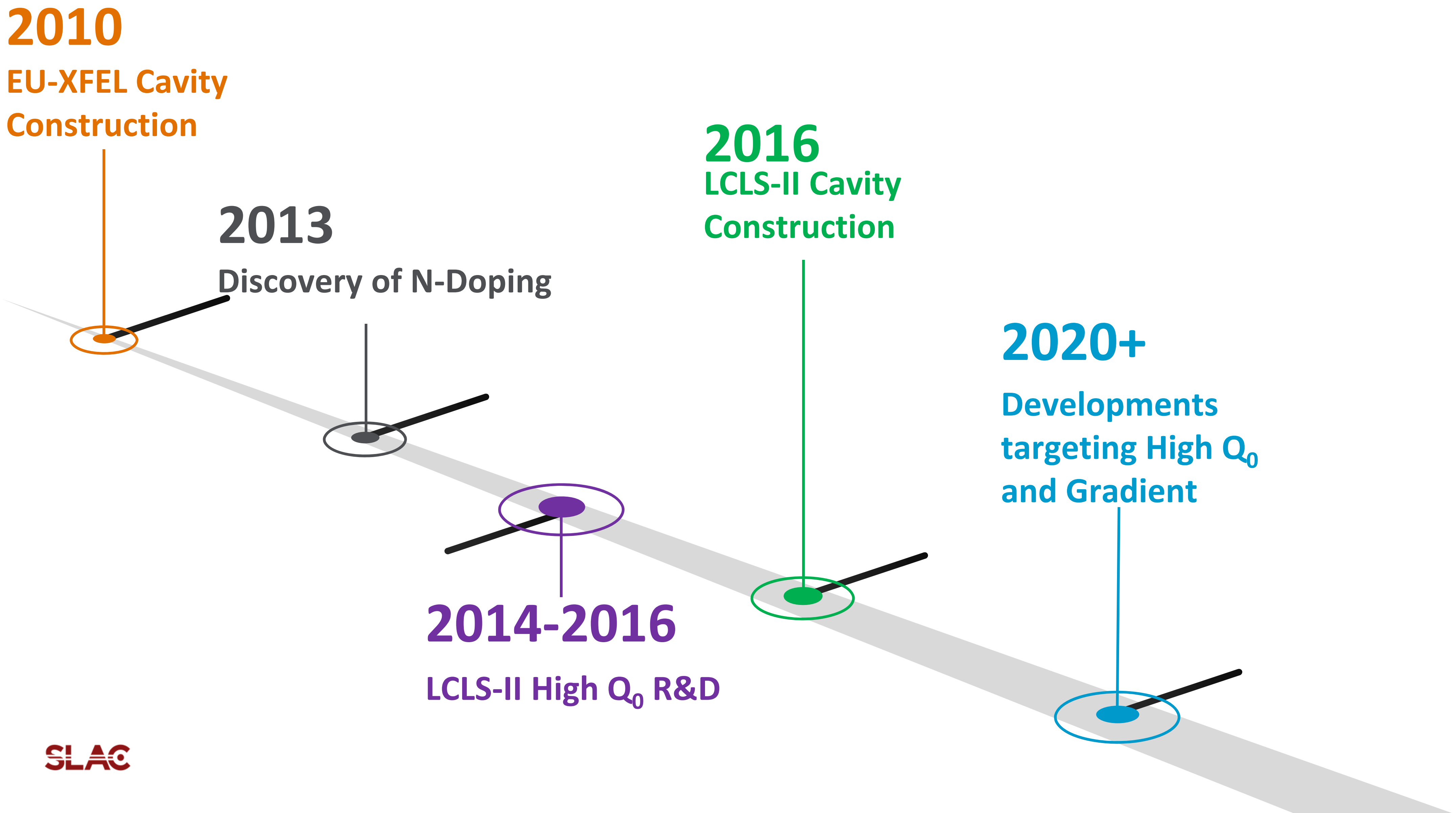
2013
Discovery of N-Doping

2014-2016
LCLS-II High Q_0 R&D

2016
LCLS-II Cavity Construction

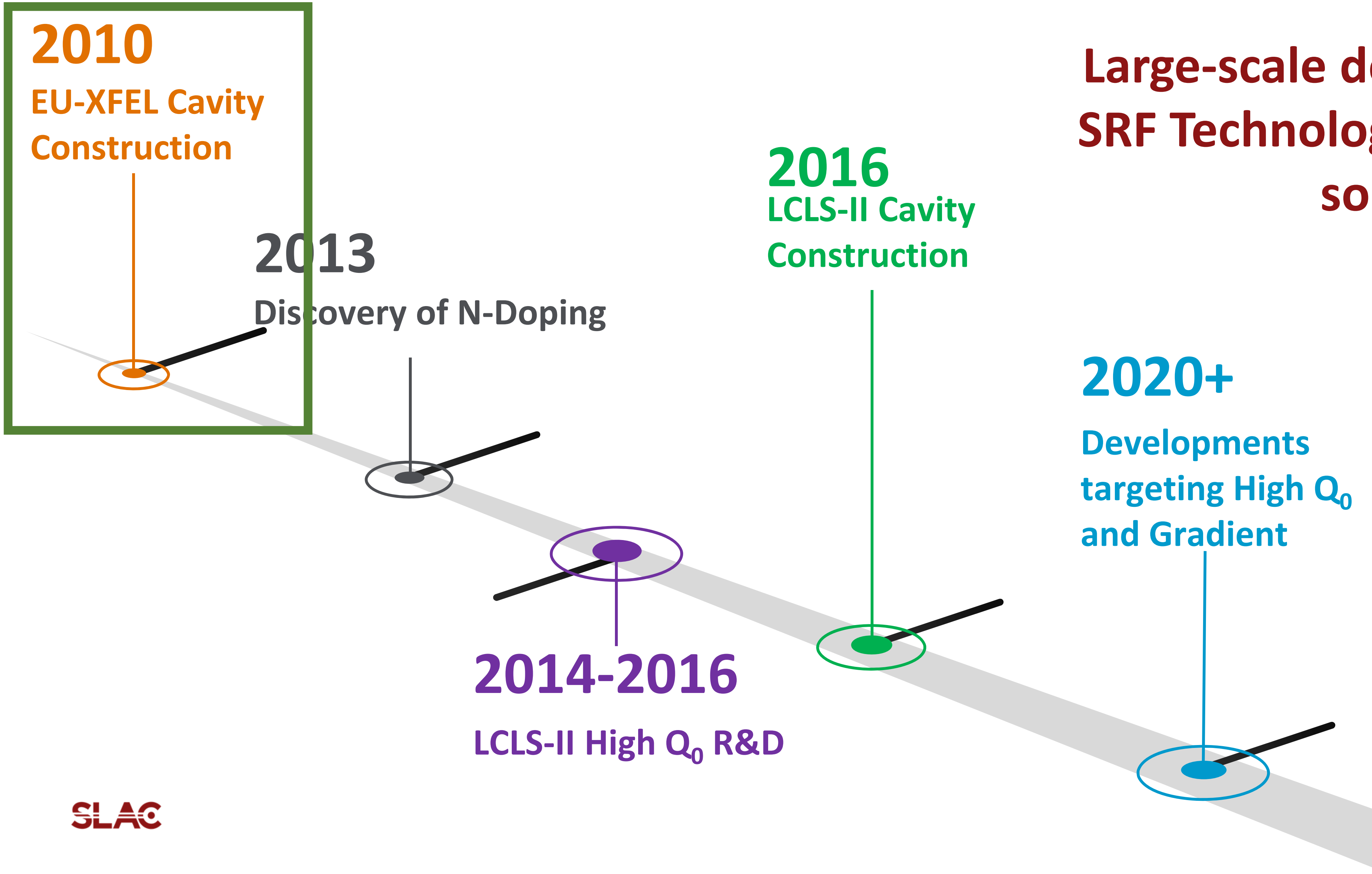


Developments in SRF Technology



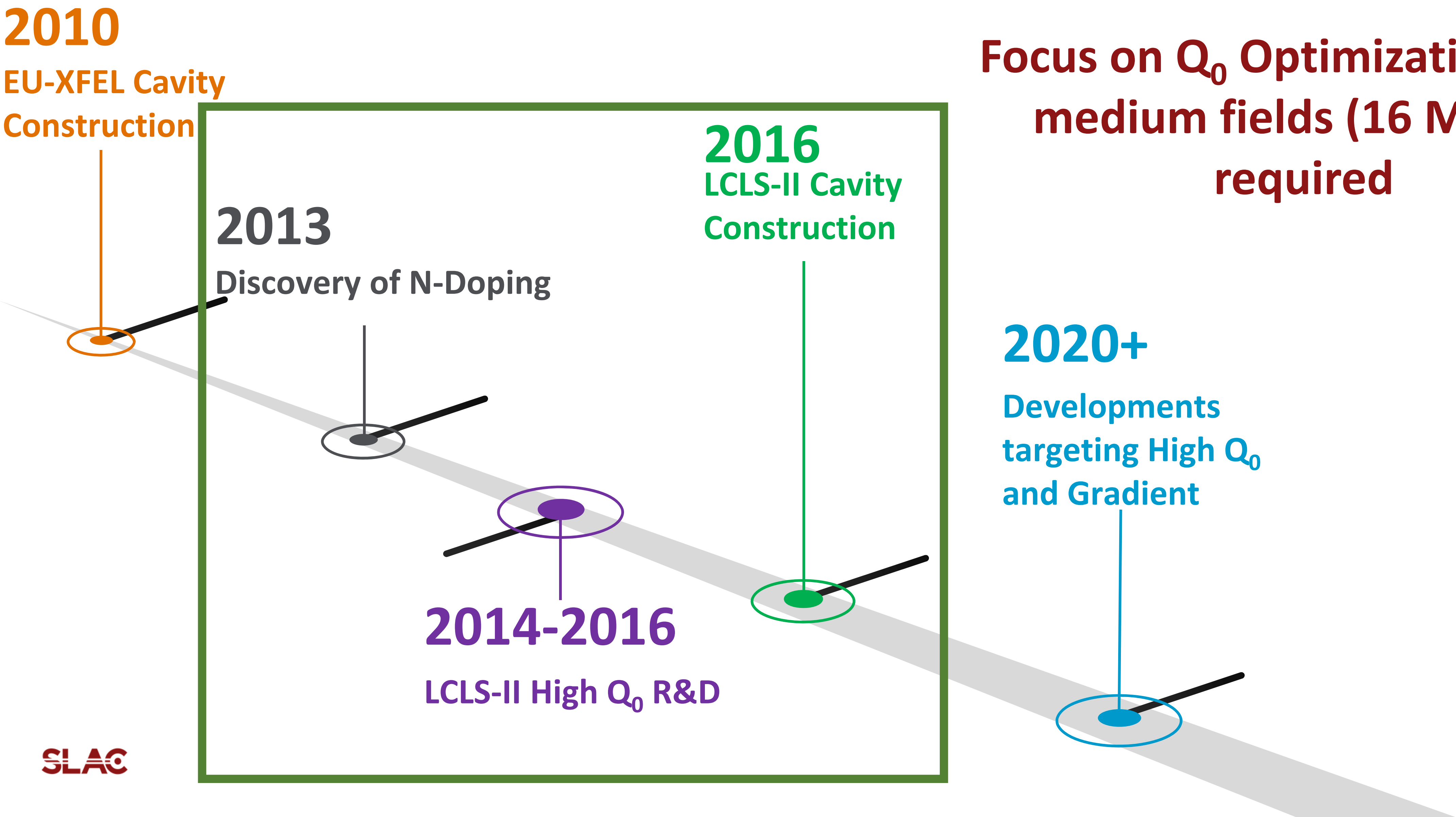
SLAC

Developments in SRF Technology



Large-scale demonstration of SRF Technology for Linac light sources

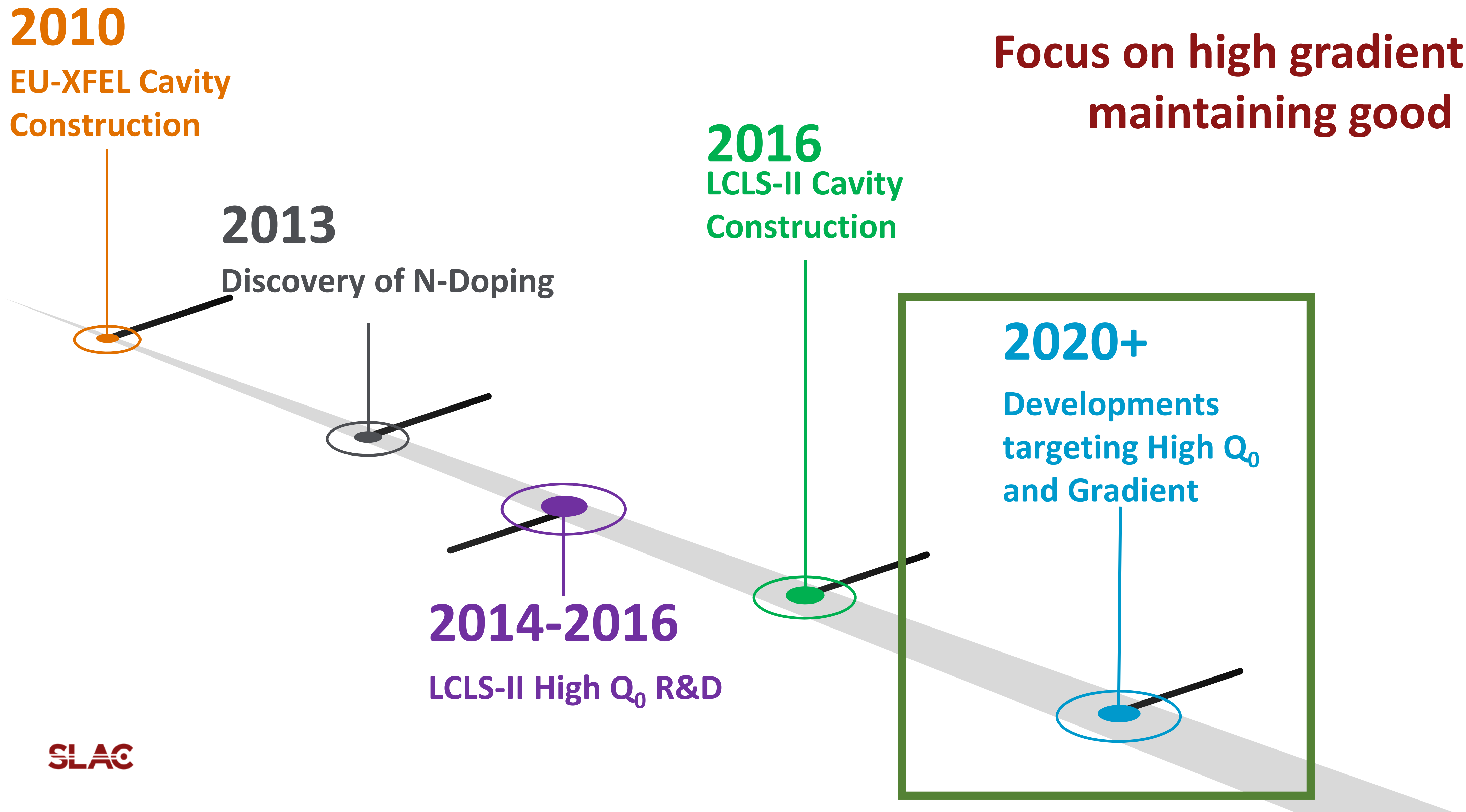
Developments in SRF Technology



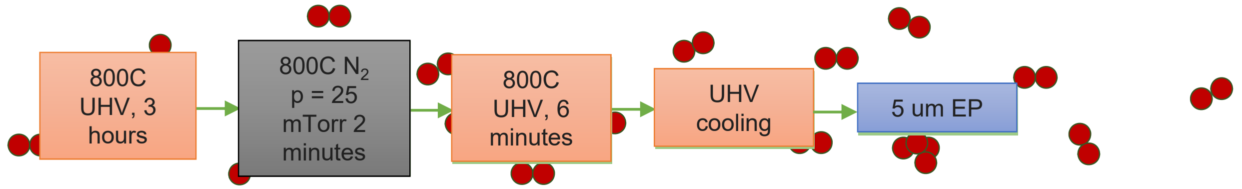
Focus on Q_0 Optimization, only medium fields (16 MV/m) required

Developments in SRF Technology

Focus on high gradients while maintaining good Q_0

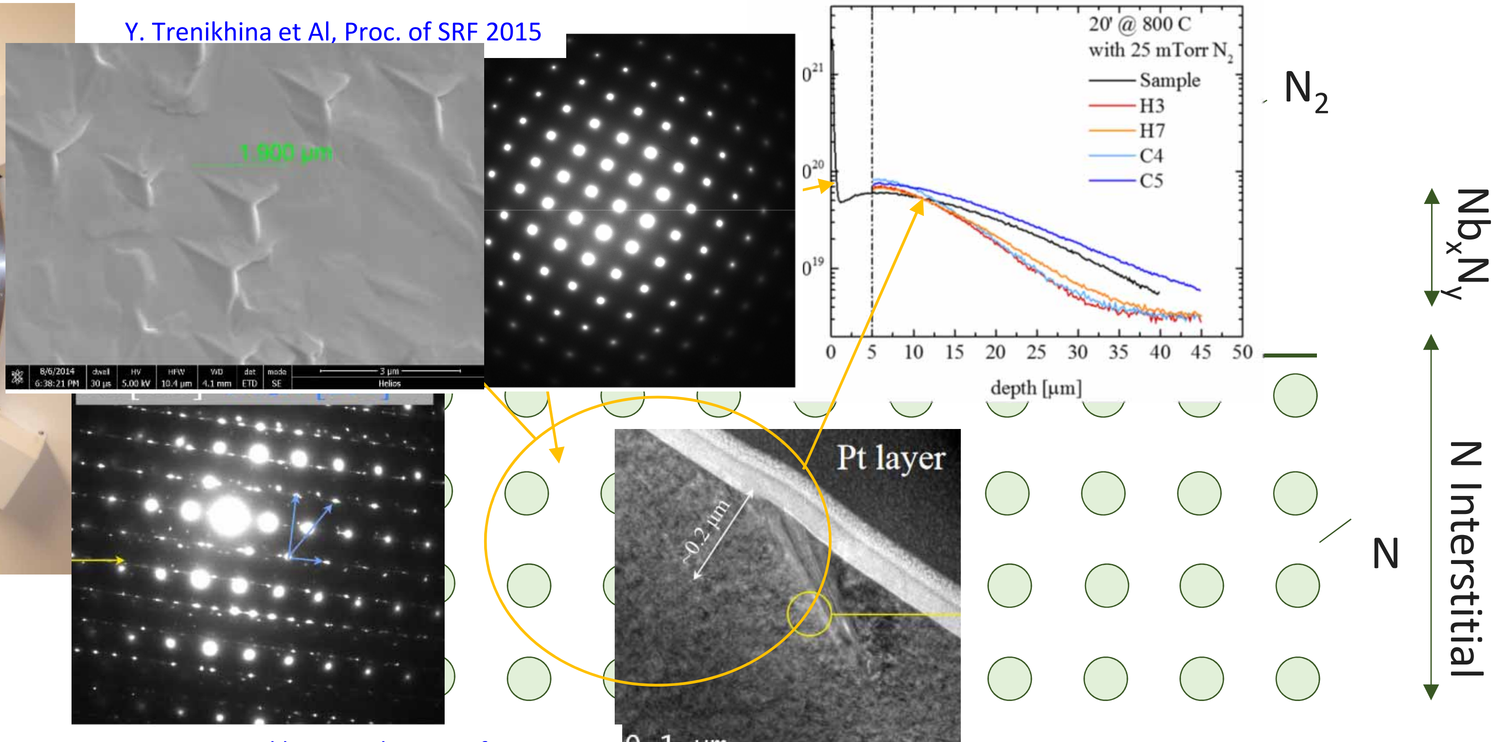


Nitrogen-Doping Process



Cornell's UHV Furnace

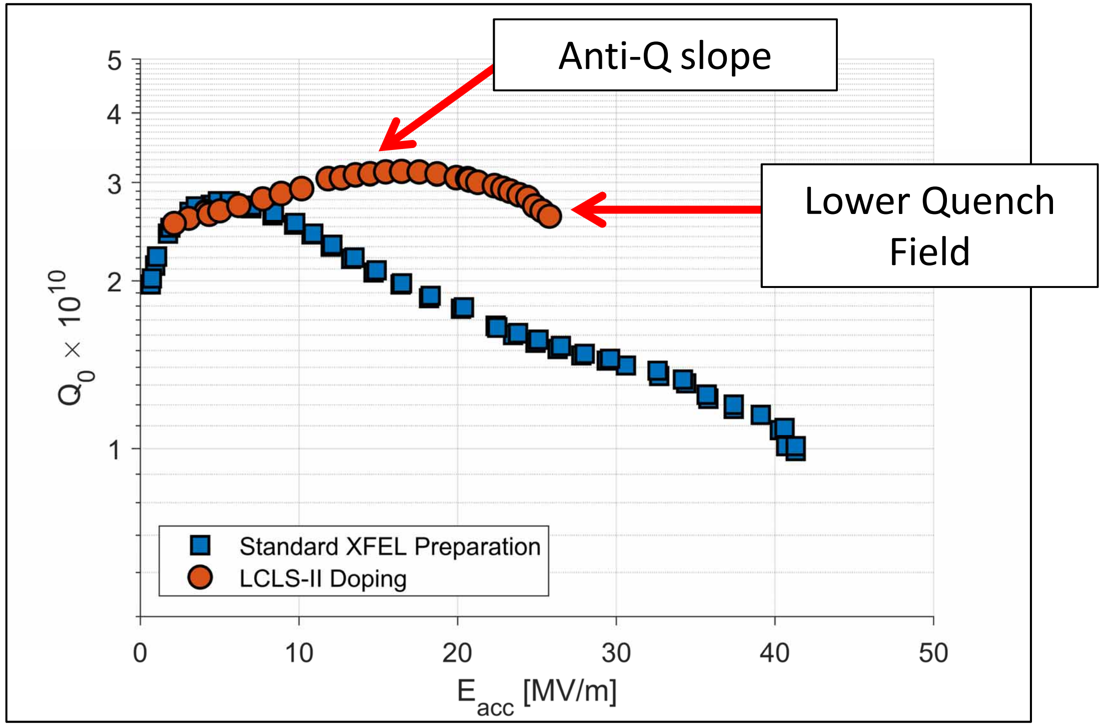
Y. Trenikhina et Al, Proc. of SRF 2015



Y. Trenikhina et al, Proc. of SRF 2015

Slides adapted from M. Martinello

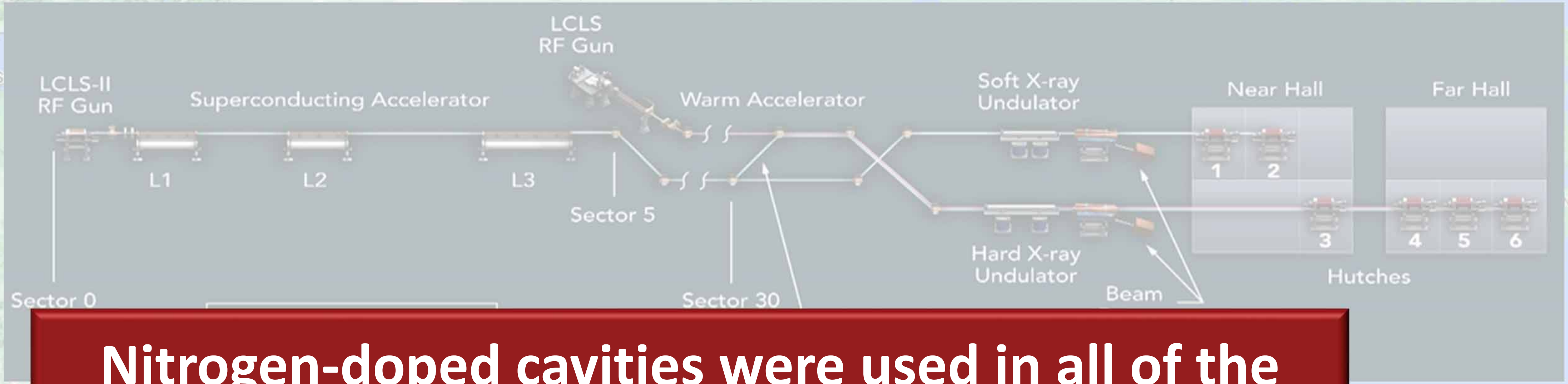
Nitrogen-Doped Cavity Performance



- Compare with standard cavities:
  - XFEL preparation typically produced cavities with a medium field Q slope starting at ~5 MV/m
  - Nitrogen-doping results in a drastic improvement in Q_0
  - MFQS disappears and an "anti-Q slope" manifests
  - Historically this would also result in a lower quench field
- Further developments in SRF technology have been based on this general concept

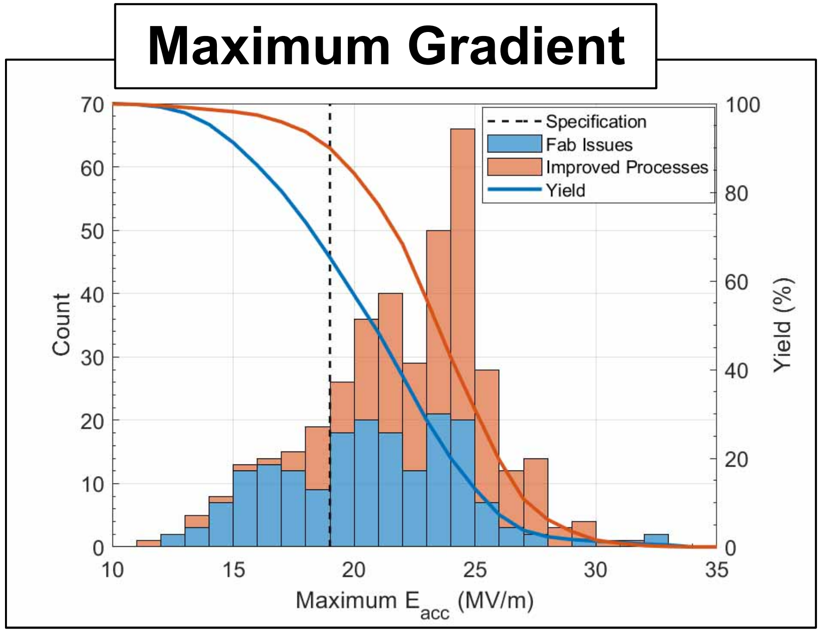
Can we reach higher Q_0?

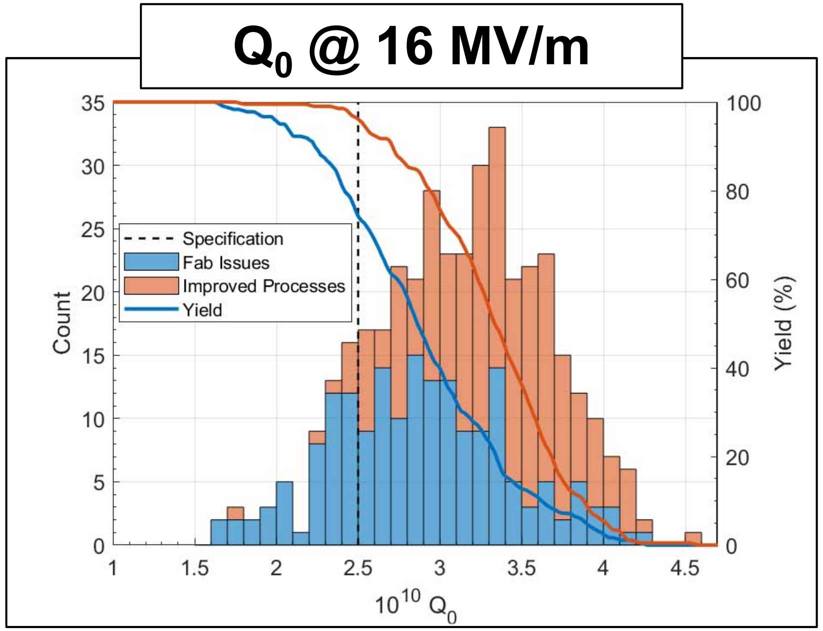
Can we increase the gradient achieved with high Q_0?



Nitrogen-doped cavities were used in all of the 1.3 GHz LCLS-II Cryomodules – first use of the new technology in an installed accelerator

LCLS-II Vertical Test Cavity Performance

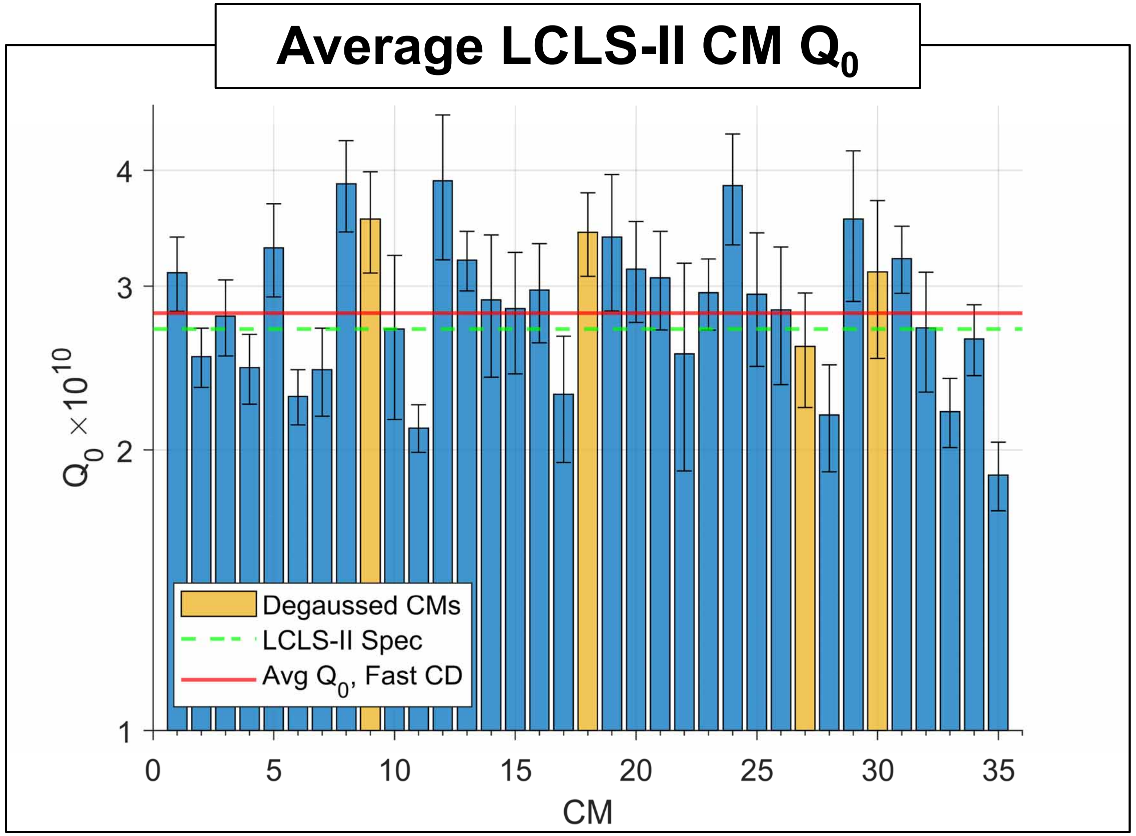




- Gradient performance typically exceeded the LCLS-II requirements in VT
- Significant improvements to processes were made throughout production which led to an increased yield
- New processes led to an average maximum gradient of **23±3 MV/m**

- Q_0 performance from the production doped cavities was excellent
- A change in heat treatment temperatures resulted in improved flux expulsion which led to consistently higher Q_0
- Able to achieve an average Q_0 of **$(3.3\pm0.4)\times10^{10}$** at 16 MV/m and 2 K

Realization of High Q_0 in an Operating Accelerator

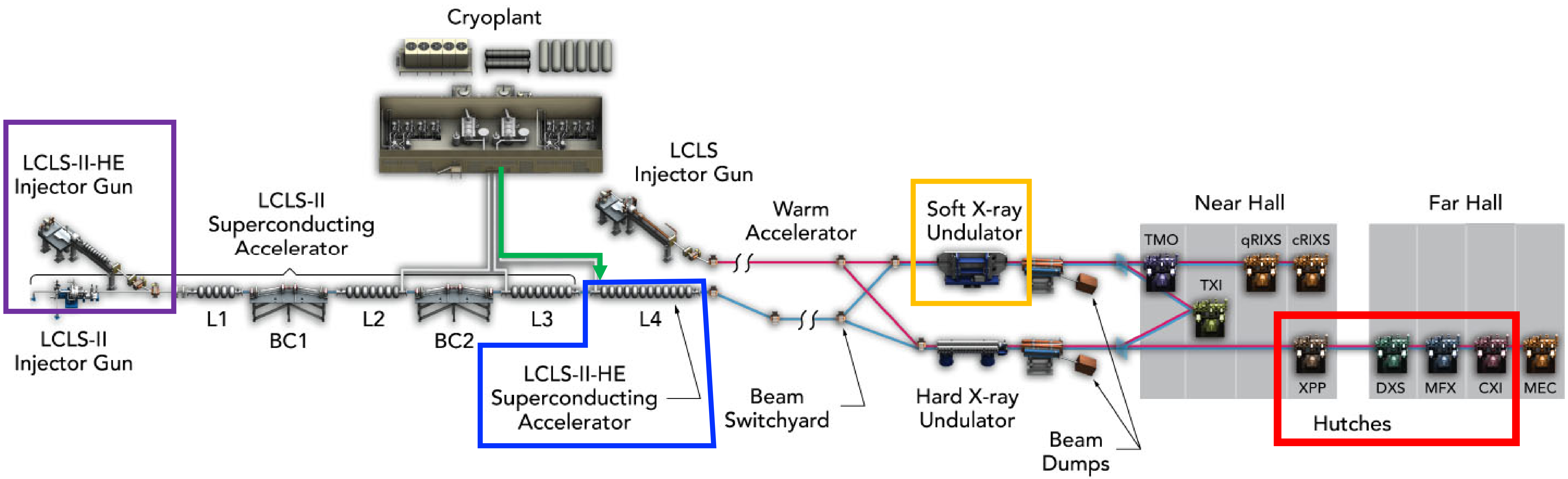


- The LCLS-II cryomodules show an **average of 2.8×10^{10}** has been observed, **exceeding the spec** of 2.7×10^{10}
- Low performers can likely be improved by additional CM degaussing

Demonstrates High Q_0 in an installed linac for the first time

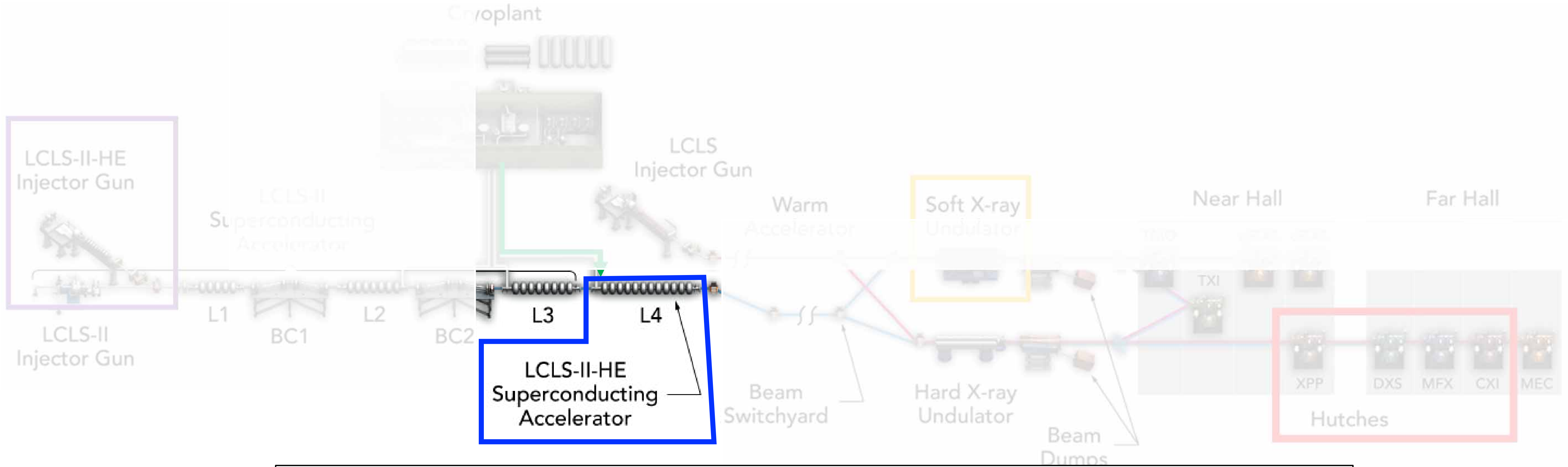
LCLS-II-HE at SLAC

LCLS-II-HE Overview



1. Add 23 additional cryomodules (L4 linac) to double the LCLS-II accelerator energy: 4 GeV to 8 GeV
2. Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac
3. New long period soft X-ray undulator
4. Upgrade the LCLS hard X-ray instruments for MHz beam and data rates
5. Design low-emittance injector and SRF gun for extended hard X-ray performance

LCLS-II-HE Overview



1. Add 23 additio
2. Install new cry
3. New long peri
4. Upgrade the L

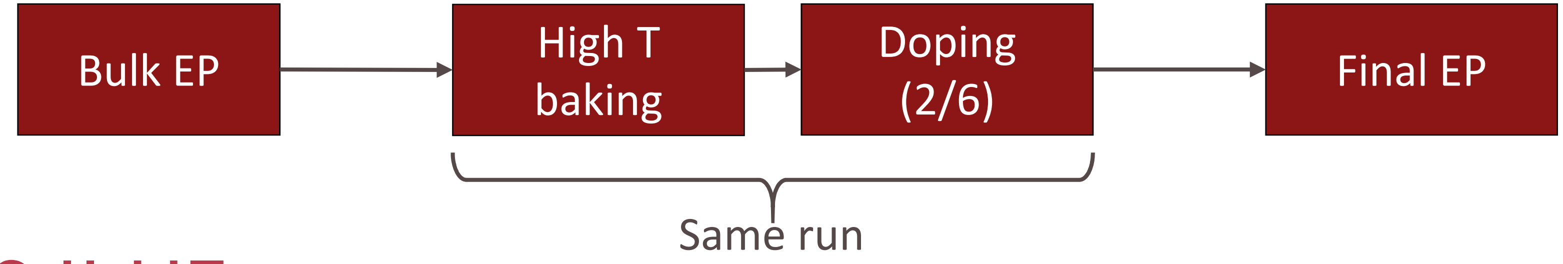
New cryomodules must operate at an average gradient of 20.8 MV/m compared to 16 MV/m for LCLS-II cryomodules:

Significant improvement in cavity performance is required

5. Design low-emittance injector and SRF gun for extended hard X-ray performance

LCLS-II-HE improved cavity processing

LCLS-II



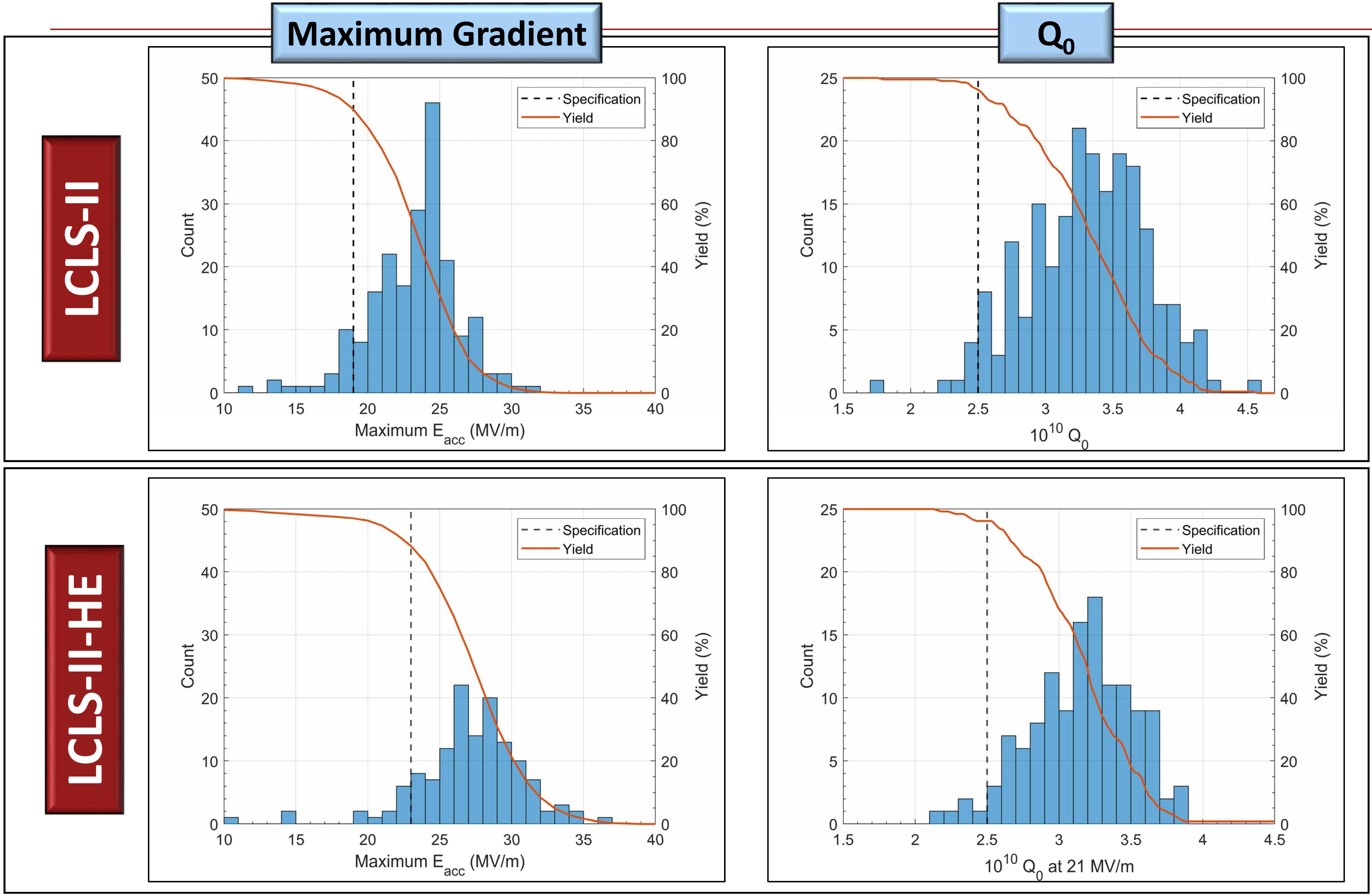
LCLS-II-HE

Additional changes:

- Continuous RGA spectrum during furnace runs
- Continuous monitoring of temperatures during electropolishing runs
- Sort cavity half-cell material by required heat treatment temperature

Slide from M. Checchin

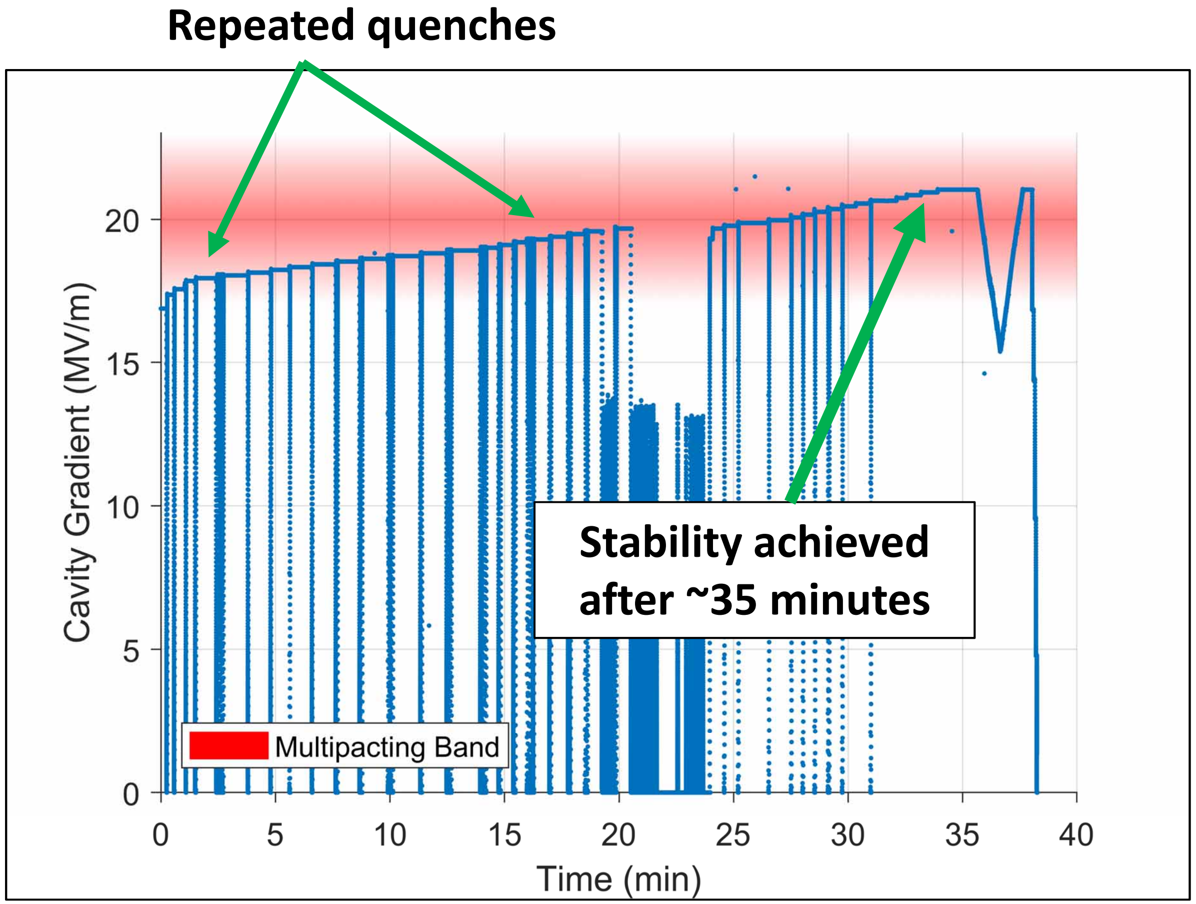
LCLS-II-HE: Cavity Performance Improvements



- Average maximum gradient **increased by ~4 MV/m**
- Average Q_0 unchanged

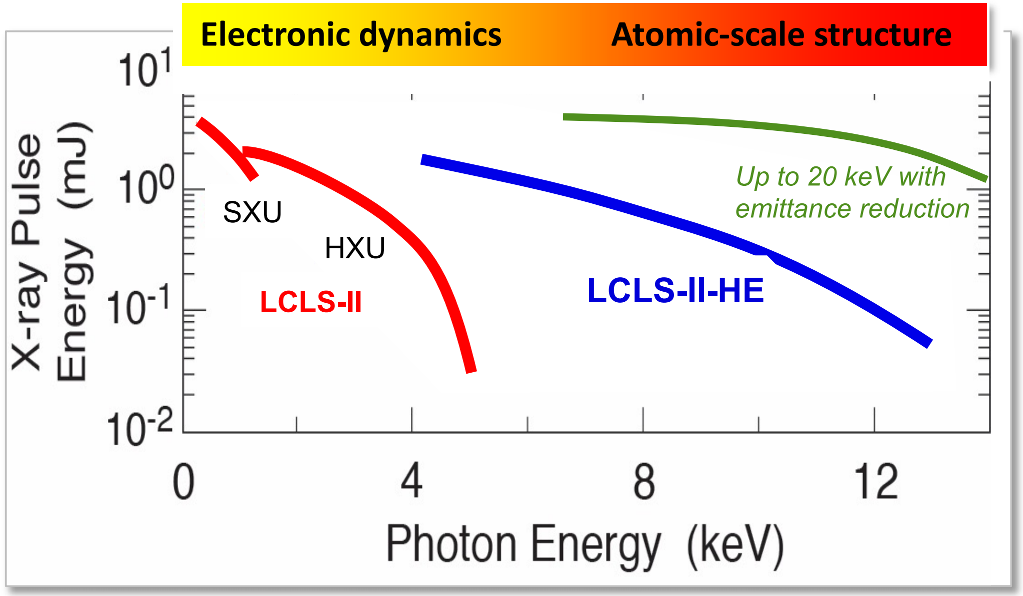
Multipacting Processing

- Multipacting identified as a gradient limitation for LCLS-II cavities late in CM production
- Observed as a short term stability at gradient in the band of 17-23 MV/m
- Processing techniques developed and tested by LCLS-II-HE team and applied to a subset of cavities in the installed linac
  - Consists of repeatedly quenching the cavity in CW mode with limited time (few seconds) for recovery
- Multipacting has not returned after >3 months – effects of processing persist through thermal cycles

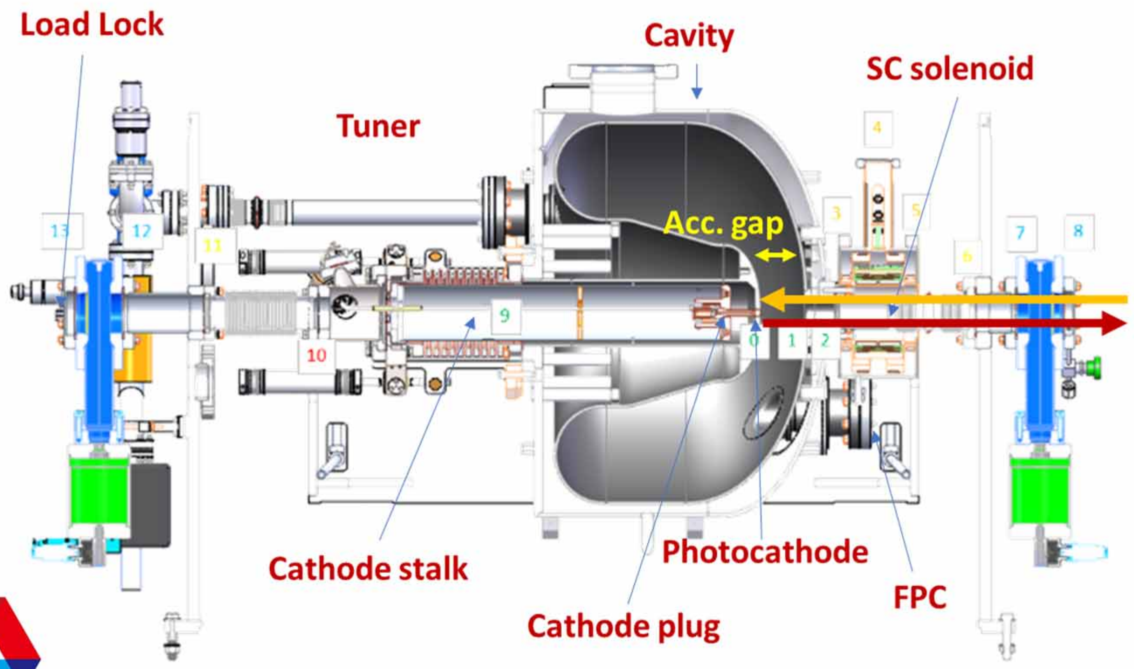


Average gradient gain of ~3 MV/m observed in 37 cavities processed

LCLS-II-HE SRF Gun - Goal 0.1 µm emittance



- Reducing emittance is the most economical path to harder x-rays
- Low emittance starts at the source – need a semiconductor cathode in 30 MV/m gradient
- R&D effort at MSU to demonstrate cavity



- Blank cavity has been assembled and tested
- Achieved 29 MV/m before Field Emission, will be retested after further EP
- Full second cavity with cathode stalk will be delivered to SLAC in 2025

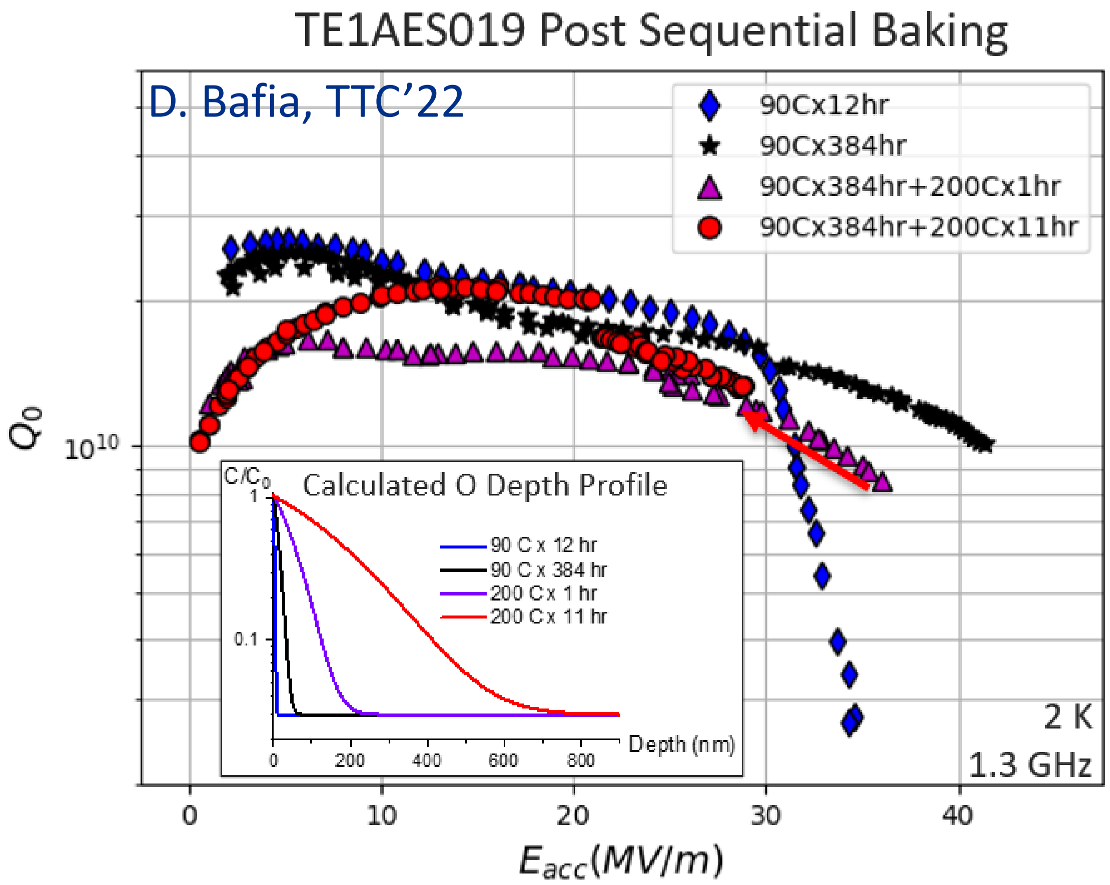
SLAC FRIB Argonne NATIONAL LABORATORY HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

SRF Developments at Fermilab

Slides courtesy of D. Bafia

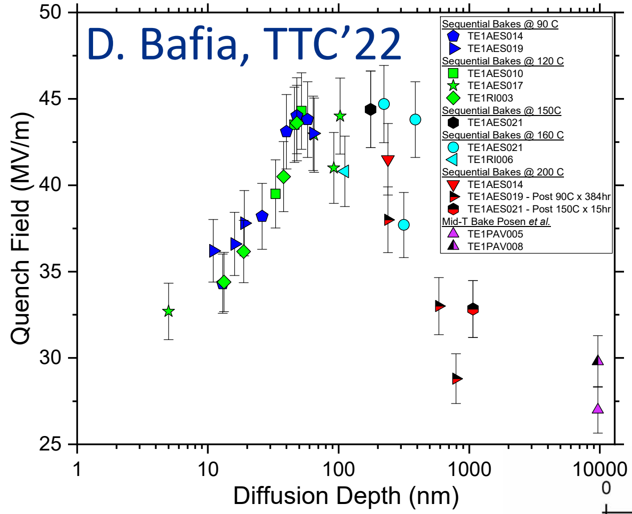
Tuning Nb SRF Cavity Performance with O Impurities

Recently learned that thermally diffused **oxygen impurities** alone can be used to tune Nb SRF cavities for **high gradient or high Q_0**!



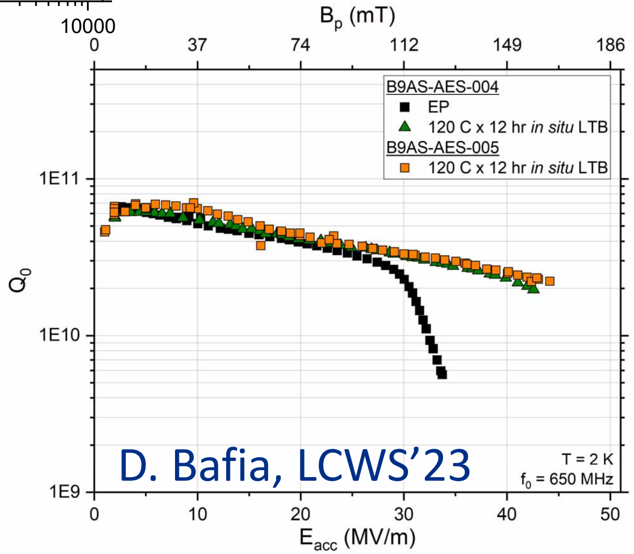
Quench Optimization Study:

D. Bafia, H. Hu



Identified **optimal oxygen profiles** for high Q_0 or high gradients

Applied findings to lower frequency cavities and obtained **near record quench fields!**

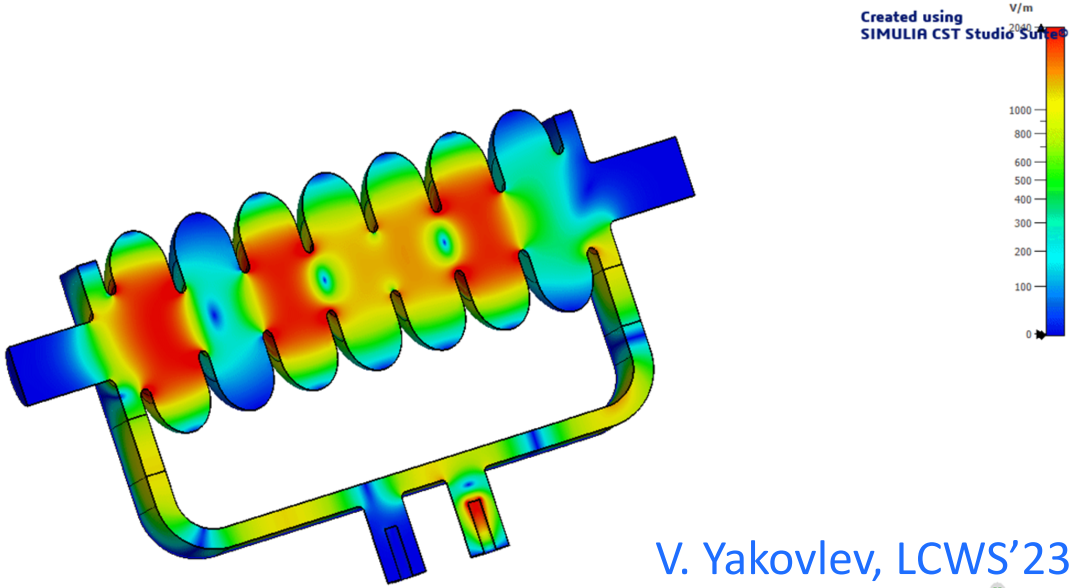


Slide from D. Bafia, FNAL

Fermilab

Extending Gradients Further with the Traveling Wave Design

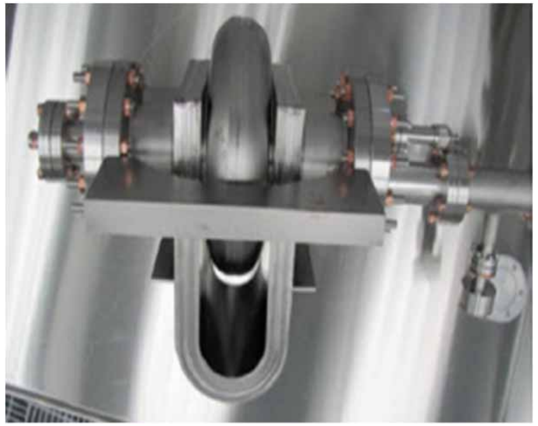
- Standing wave Nb cavities limited E_{acc} by H_{sh}
- Alternative: Niobium traveling wave structure
  - RF power returned *via* feedback Nb waveguide → Lowers peak fields in cavity
  - Possible to achieve **E_{acc} > 70 MV/m!!**

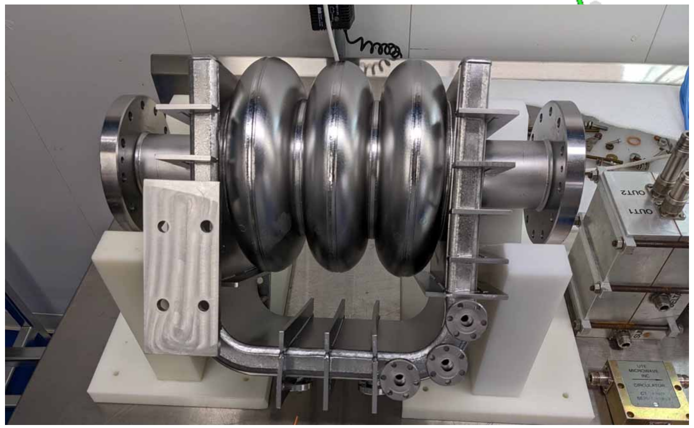


V. Yakovlev, LCWS'23

Current Status:

- 1-cell: designed, treated (BCP), and tested
  - **Achieved 26 MV/m** in RF testing
- 3-cell: designed and treated (BCP)
  - Tuning just completed
  - RF testing scheduled for this summer
  - TW operation demonstrated at room temp!
- 0.5 m structure currently being designed in collaboration w/ Cornell





*Euclid Techlabs DOE SBIR DE-FG02-06ER84462 and DE-SC0006300.

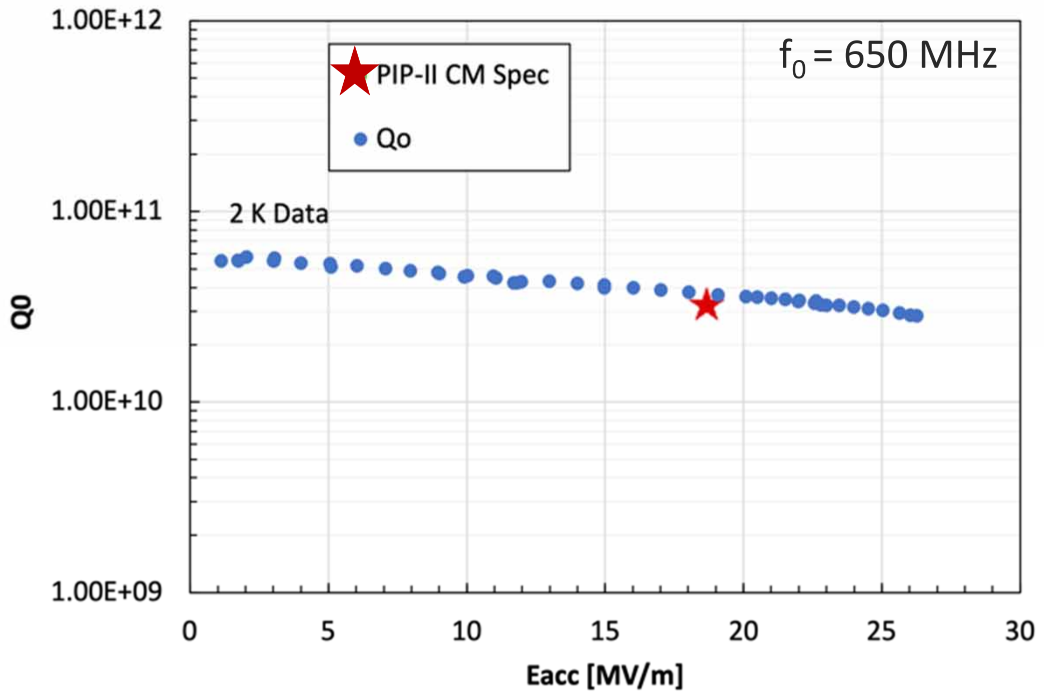
Slide from D. Bafia, FNAL

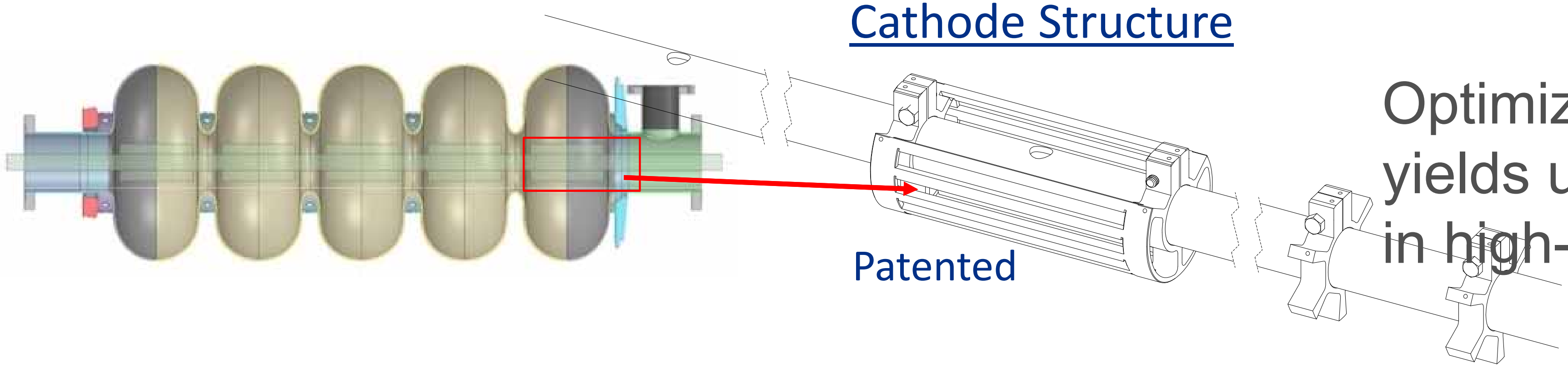
Fermilab

Improving 650 MHz Performance Further *via* Optimized EP

V. Chouhan, SRF'23

- Proper electropolishing (EP) is critical in enabling excellent cavity performance
  → Smooth surface, minimal uptake of H
- Developed a **novel cathode** and **optimal EP parameters** for 5-cell 650 MHz cavities for PIP-II





Optimized design and parameters yields unprecedented performance in high-β 650 MHz EP'd cavities!

Slide from D. Bafia, FNAL

Fermilab

SRF Activities and Plans at DESY

Slides courtesy of L. Steder, M. Wenskat, and E. Vogel

High Duty Cycle options for EuXFEL

we aim for a wide range of operation modi

- Preparation for **possible EuXFEL upgrade 2030+**
  - two-fold machine: High Duty Cycle (HDC) including CW mode in parallel to pulsed mode
  - upgrade roadmap depending on overall strategy of DESY
  - exchange of up to 17 accelerator modules: need for about 160 new 9-cell SRF cavities

- SRF technology R&D @ DESY
  - prepare **new generation of experts** for series production of SRF cavities and modules
  - include state of the art processes and **lessons learnt** e.g. at EuXFEL, LCLS II-HE and SHINE
  - TESLA cavities
    - revision and **upgrade of EuXFEL cavity specification**
    - development of new surface treatment (mid-T) parameters for optimized cavity performance
  - SRF accelerator modules
    - **extensive HDC and CW tests** of standard EuXFEL modules
    - revision of e.g. 4K-shield and coupler parts

furnace installation of two R&D cavities

Pushing Niobium to its limits – and beyond

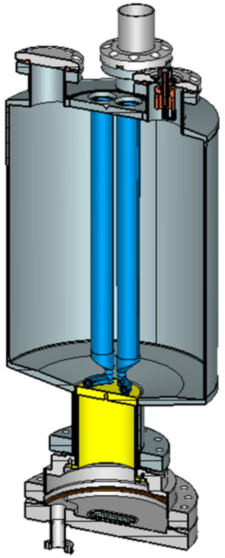
project-oriented R&D hand in hand with fundamental R&D

- To enable the EuXFEL upgrade 2030+, we need to
  - **reliably** achieve $Q_0 \geq 2.7x10^{10}$ @ 16-20 MV/m **AND** $E_{acc} \approx 30$ MV/m for pulsed mode
    → recipe not existing yet
  - **transfer** the respective recipe **to industry**
    identify key parameters of the process for technical description

- To achieve this: **project-oriented** R&D hand in hand with **fundamental** R&D
  - systematic RF studies on cavities (1-cell and 9-cell) and samples (Quadrupole Resonator)
  - material studies to understand (sub)-surface processes & links to RF performance
  - study magnetic behavior of cavities and samples, e.g. with new B-mapping system

- **Sustained SRF accelerator technology** needs to address generic R&D:
  - coating alternating insulator & higher T_c superconductor onto Nb "*SIS*" using atomic layer deposition (ALD)
    We already developed recipe on samples, successfully coated cavities with insulator
  - **ultimate goal**: >70 MV/m with a Q_0 of $1x10^{10}$ and at 4K

ALD coating



Quadrupole Resonator

SRF photoinjector status at DESY

present R&D status and activities (8/2023)

Goal:

- CW "pancake" bunches to match L-band linac w/o buncher
- peak-on-axis gradients above 40 MV/m required

Key R&D items:

- surface treatment of "special" geometry for high gradients
  https://www.ipac23.org/preproc/pdf/WEPA145.pdf
- cathode and its insertion w/o causing contamination

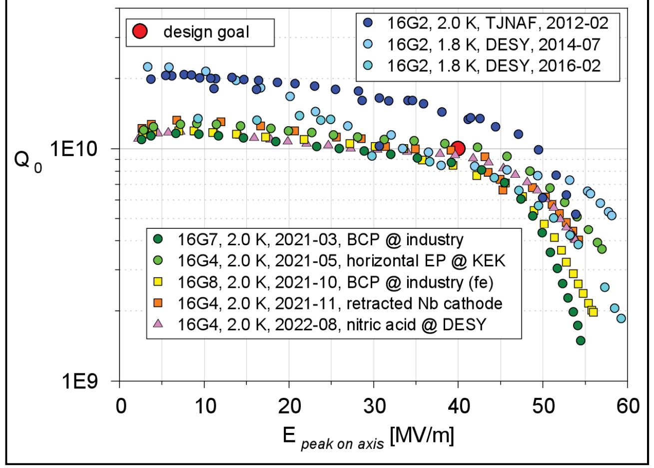
Concept for the cathode:

- screwed in cleanroom to the cavity backside
- metal as cathode material with QE beyond 10^{-4}

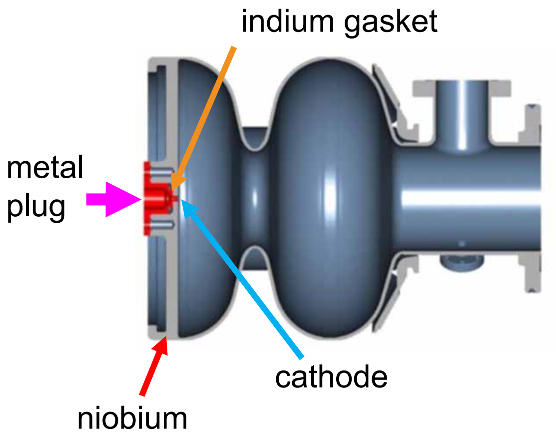
Status of the R&D:

- typical peak on axis gradients around 55 MV/m achieved!
- some of the metal cathodes being studied and tested:
  - Nb plug with Pb coating: better adhesion required
  - nano-structured Pb for plasmonic state QE enhancement
  - surface treated Cu plug
- work in progress and in planning phase:
  - cold integration like He-vessel, tuner, cryostat, …
  - test stand with beam line to study beam properties

vertical test results



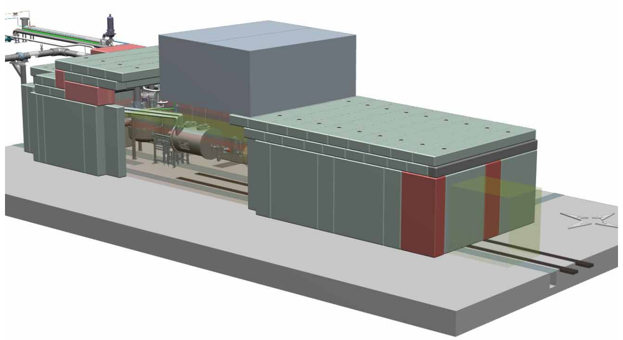
"full metal" SRF gun cavity



several generations of cavities

SRF photoinjector test stand Ts4i

purpose: testing cold integration, cathodes in SRF cavities, alignment, beam quality, beam stability, CW operation…



Summary & Outlook

- Advancements in SRF Technology have accelerated over the last 15 years due to investments from new light sources such as EU-XFEL, LCLS-II, and LCLS-II-HE
- Nitrogen-doping paved the way for a new understanding and method for achieving high Q_0 in SRF cavities
- The boundaries of performance continue to be pushed by future projects, particularly light sources
- LCLS-II-HE R&D has pushed standard nitrogen-doping cavity performance to new levels
- Fundamental developments at Fermilab and DESY continue to improve our understanding and open the door for better performance
- SRF Guns are in development around the world with a goal of lowering emittance for harder x-rays
- Developments continue around the world with other projects not mentioned here, particularly SHINE in China
- Performance improvement has no sign of slowing down!