ASET Seminar

Recent Advances in Normal-Conducting Radiofrequency Linacs

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& Argonne National Laboratory (ANL)

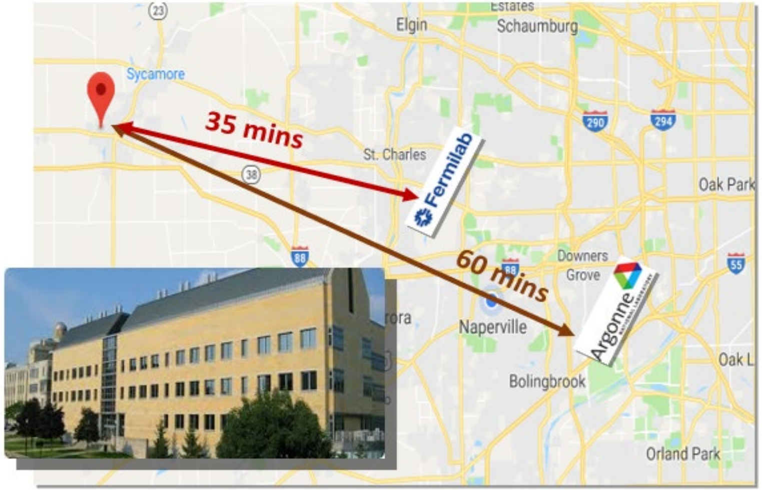
November 1, 2024
Michigan State University

Argonne NATIONAL LABORATORY

NIU Northern Illinois University

Hello from your friends at the CAST Traineeship

- Accelerator and Beam Physics at Northern Illinois University
  - We co-run the Chicagoland Accelerator Science Traineeship (**CAST**) with Illinois Institute of Technology (IIT)
  - Many students stationed at Argonne (including the Argonne Wakefield Accelerator, **AWA**) and Fermilab



Outline

- Normal-conducting RF (**NCRF**) accelerators
  - Where are they used? How to accelerate?
- Quest for high-gradient compact NCRF accelerators
  - Towards the "holy grail": Understanding the field/gradient limitations from **RF breakdown**
- Overview of recent advances in pulsed NCRF linacs
  - Innovative approaches to **various aspects** of NCRF accelerators
  - Corresponding **collider proposals** based on some advances
- Future applications
  - Colliders, light sources, industrial and medical applications, …

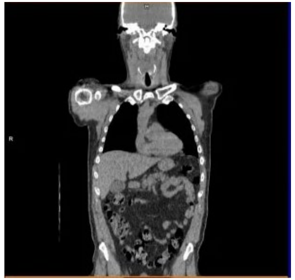
Exciting time for NCRF linacs towards various applications!

Where can you find accelerators?

- Industrial and societal applications:
  - About 30,000 accelerators in use world wide, with sales >$2B/yr

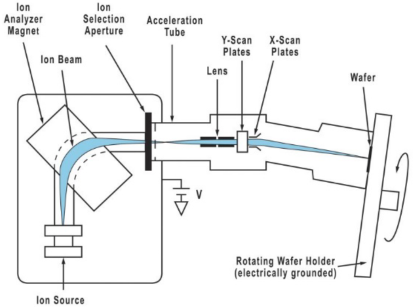
Shrink-Wrapped Turkeys

Cancer therapy

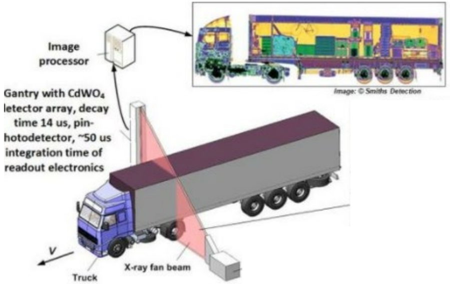


Medical Imaging

Studying cultural artifacts



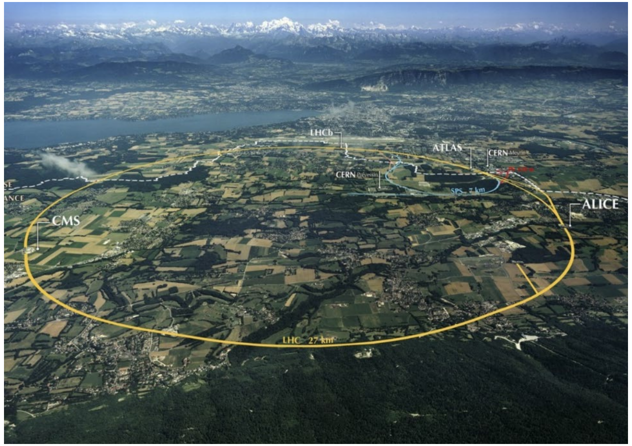
Ion Implantation



Cargo Inspection

Where can you find accelerators?

- Science discovery:
  - High Energy Physics (HEP)
  - Basic Energy Sciences (BES)
  - Nuclear Physics (NP)



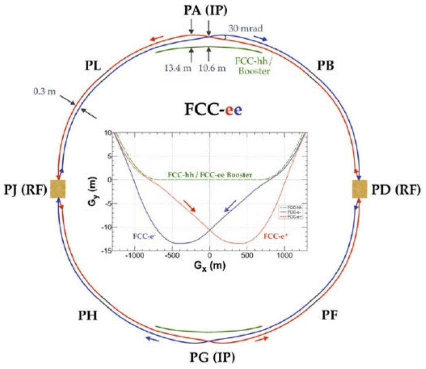
Large Hadron Collider (LHC)

Advanced Photon Source (APS)

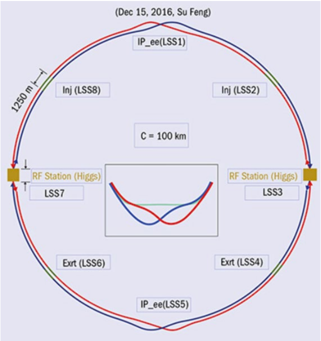
Right here ☺

Future HEP colliders: what's next after LHC?

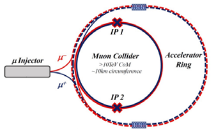
- "Examples of future colliders on the menu



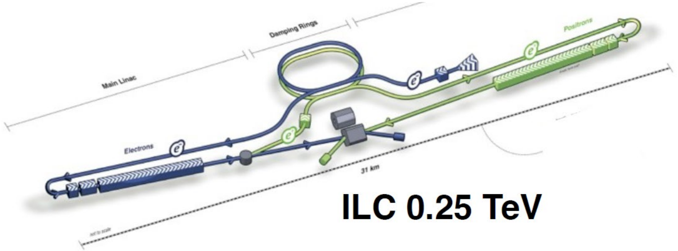
FCC-ee 0.24 TeV
FCC-hh 100 TeV
FCC-eh 3.5 TeV



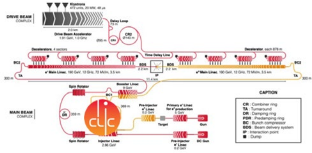
CEPC 0.24 TeV
SPPC 125 TeV
SPPC-CEPC 5.5 TeV



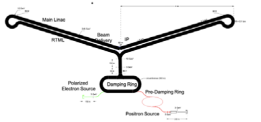
MC 10 TeV



ILC 0.25 TeV



CLIC 0.24 TeV

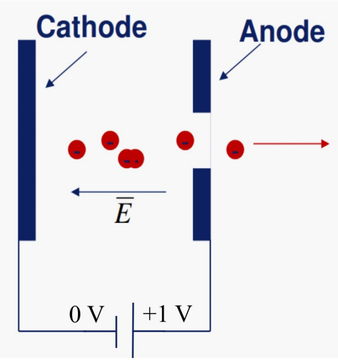


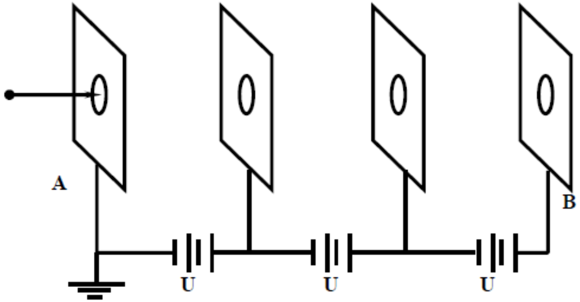
CCC 0.25 TeV

- "Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years**" – 2023 P5 report

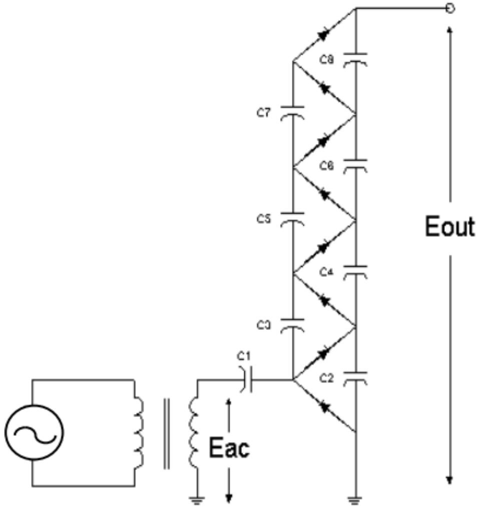
Direct-current (DC) accelerator

- Electrostatic acceleration

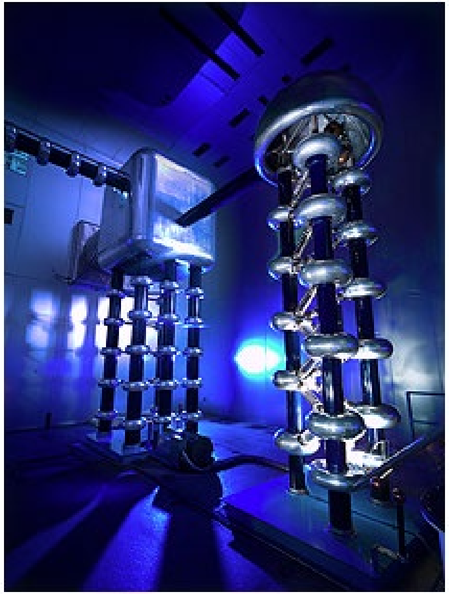




- High-voltage acceleration by stacking
  - e.g. Cockcroft-Walton generator



$E_{out} = N_{stage} E_{ac}$

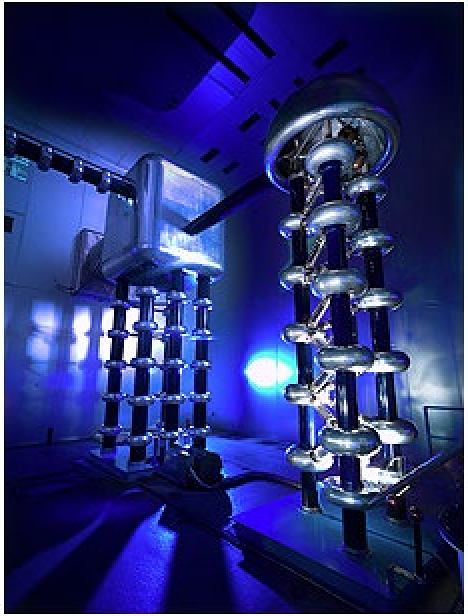


@Fermilab

But the photo is actually taken from-

So long, Cockcroft-Walton

August 21, 2012 | Joseph Piergrossi



"People who work on these things have come to love them, but it's time to move on and modernize.“

https://history.fnal.gov/historical/accelerator/so_long.html

Limitations of DC accelerators

- Electric field limited by "electrical breakdown"
  - Sparking electric field limits (Kilpatrick model)
    - About 10 kV/cm, or 1 MV/m
  - Large size
  - Exposure to high-voltage terminals

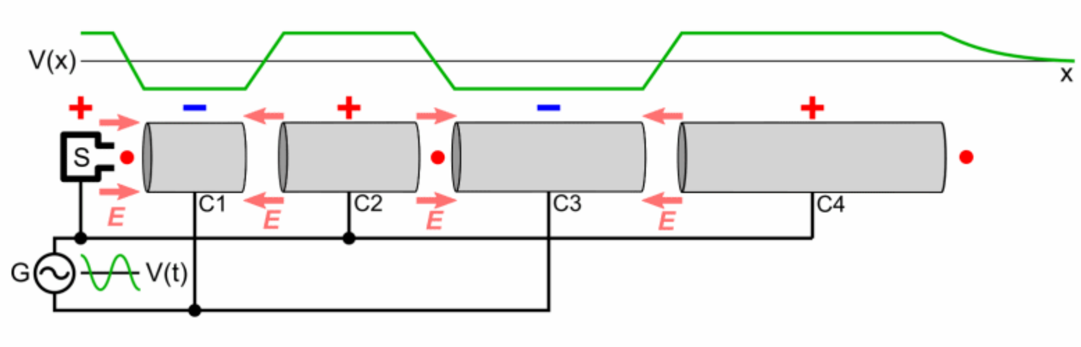
- DC accelerators are still good for applications which prefer/require:
  - Simplicity
  - A steady environment
  - Continuous beam

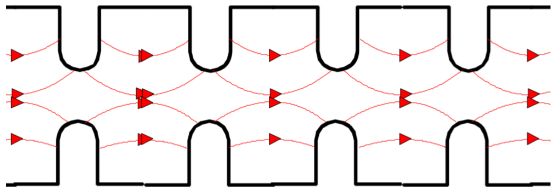
RF Acceleration

- RF acceleration allows higher energy and higher efficiency in smaller (more compact) accelerators
  - Sinusoidal electric field
  - Bunched beam to occupy a small fraction of the wavelength
  - Beam can gain energy when positioned at the correct phase
- Accelerating cavities need to provide a longitudinal electric field
  - Lorentz force

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

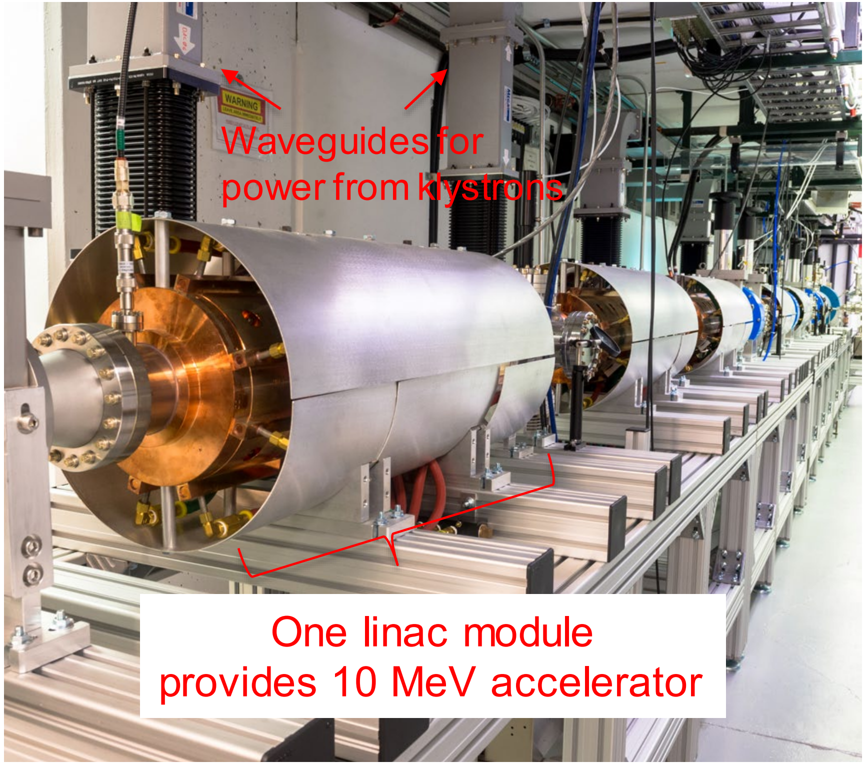
  - B field cannot provide acceleration
  - E field can provide acceleration



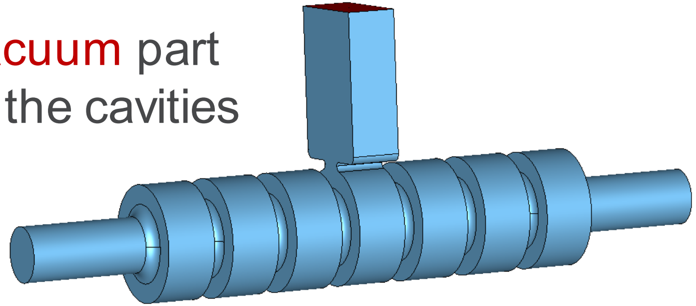


Electric field plot

Example: L-band (1.3 GHz) linac at AWA

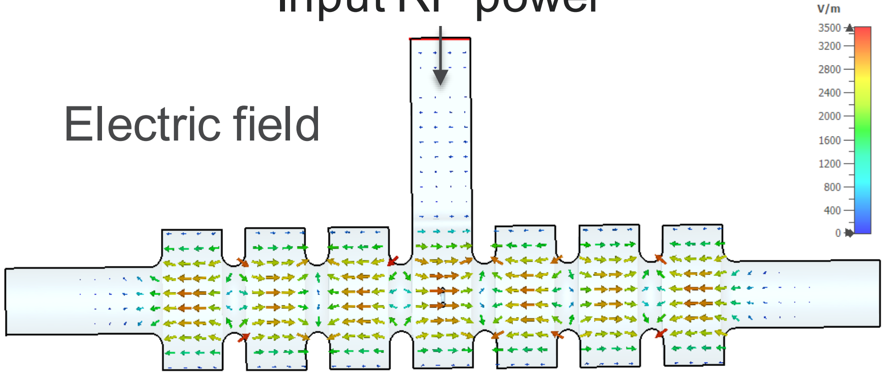


Vacuum part
of the cavities



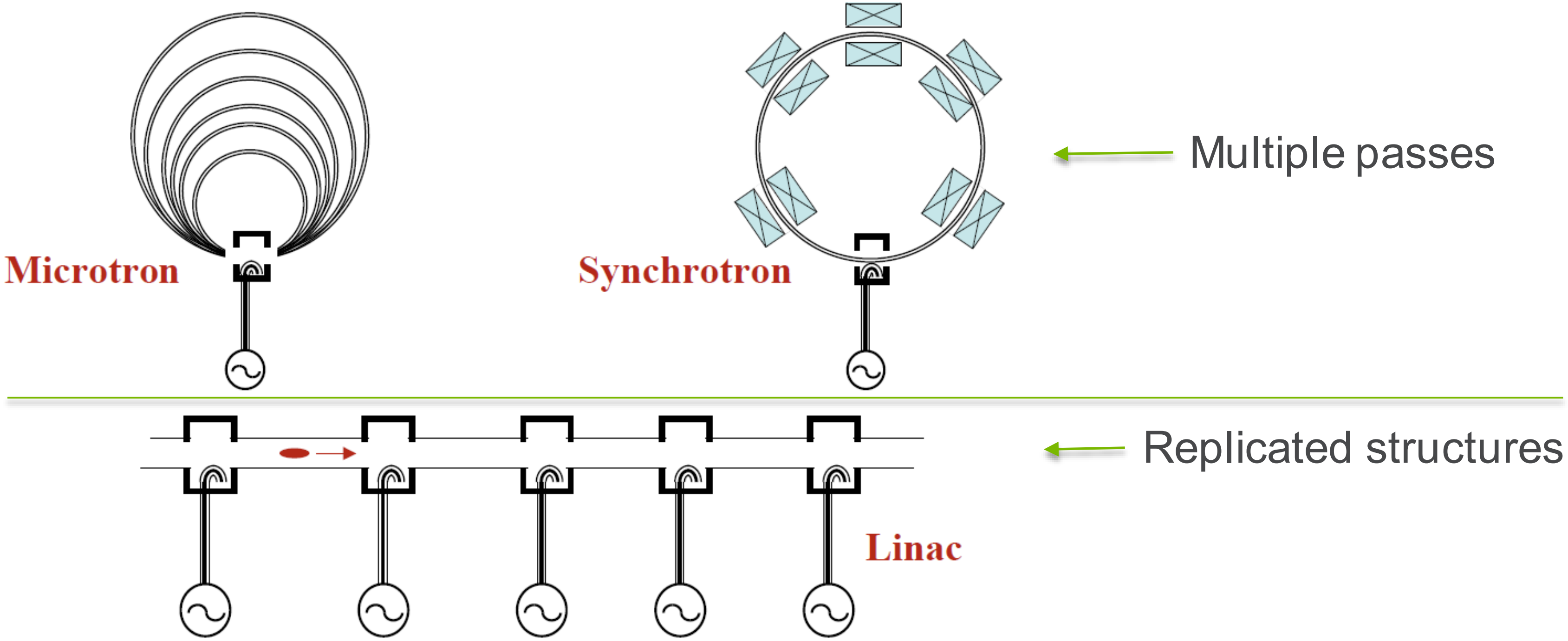
Input RF power

Electric field



How to use RF structures in an accelerator?

- Two different schemes:
  - RF acceleration in circular vs. linear machines



Linear RF Accelerators

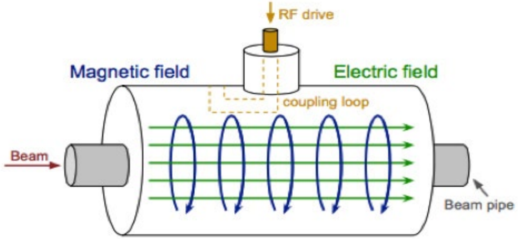
Stanford Linear Collider
2 miles, 100 GeV collision energy for *e+*/*e-*

(now mostly used as a laser)

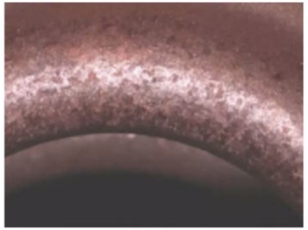
Energy = Length × **Gradient**

High gradient → Compact linear accelerators

High-gradient acceleration using NCRF structures



- NCRF structures: **copper** structures (traditionally) at **room temperatures** (water cooled traditionally)
- High gradient → **Compact** linear accelerators
  - (Other considerations than the gradient: short- and long-range wakefield, RF power, beam loss, cooling…)
- Limiting factor in high-gradient operation: **RF breakdown**
  - Accelerating gradient currently limited to 10-100 MV/m in conventional NCRF accelerators
- RF breakdown is unwanted
  - Occurs with relatively high surface field
  - Dark current, outgassing or plasma discharge, visible flash
  - Possible irreversible structure damage
- Often presented as breakdown rate (BDR)

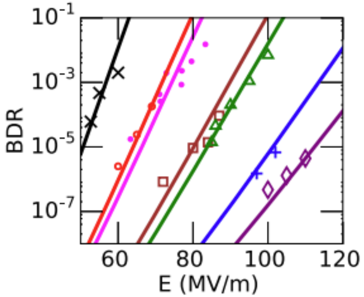


Breakdown-induced pitting in a copper structure

Physics understanding of RF breakdown—

- Greatly deepened through both theoretical and experimental studies
  - Modeling
    - Analytical models (vacancy/ dislocation…) and simulations

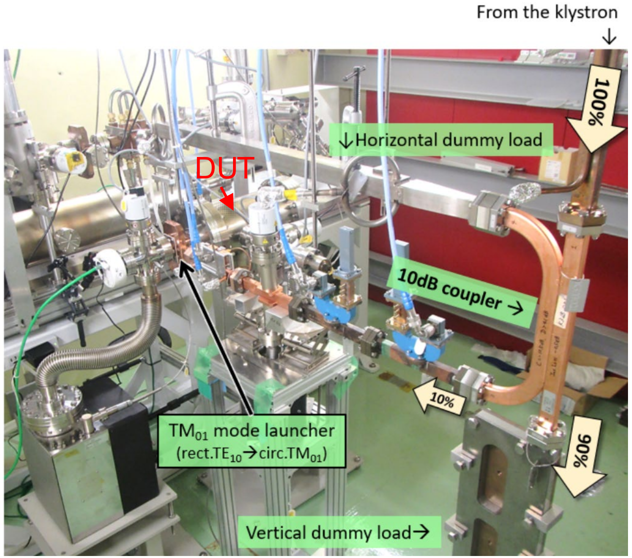
Stochastic model describing breakdown nucleation fitted with structure testing data



E. Engelberg *et al.*, PRL 120, 124801 (2018)

  - RF breakdown test

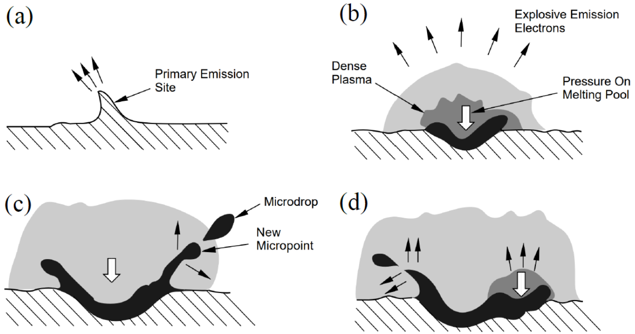
Nextef2 @KEK, Japan



- While the physics mechanism is not fully understood, we can make predictions about structure performance based on empirical understanding of a few factors—

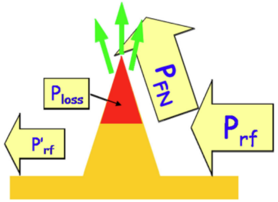
Field quantities that matter in RF breakdown

Electric field: field emission

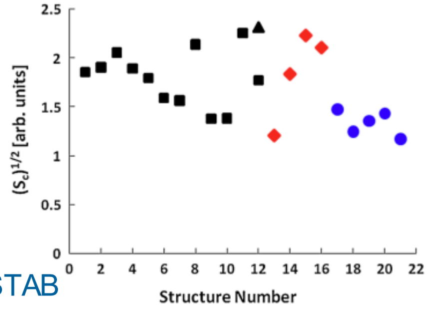


J. W. Wang and G. A. Loew

Power flow / Local power coupling



A. Grudiev, et al., PRSTAB 12, 102001 (2009)

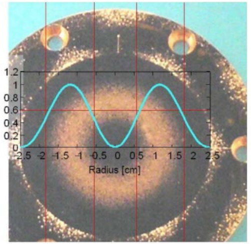


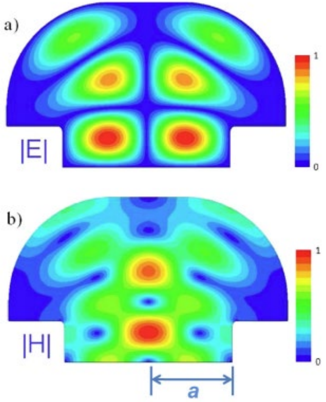
$$S_c = \|\Re\{\bar{S}\}\| + g_c \cdot \|\Im\{\bar{S}\}\|$$

$$E^* = E_0 - f(E^*) R_{bd} / l_{ant}$$

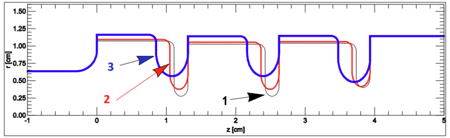
J. Paszkiewicz, et al., 2022

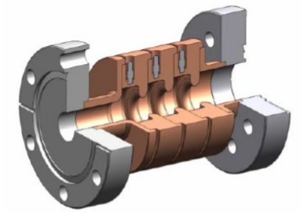
Magnetic field: pulsed heating

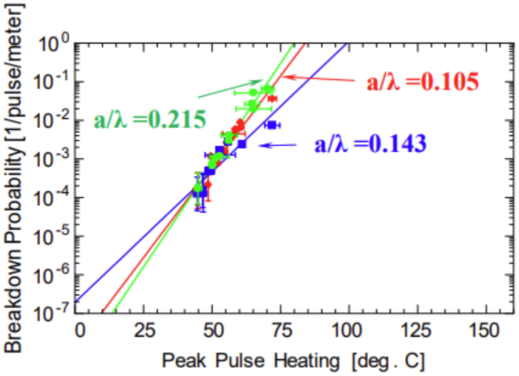




L. Laurent, *et al.*, PRSTAB 14 041001 (2011)







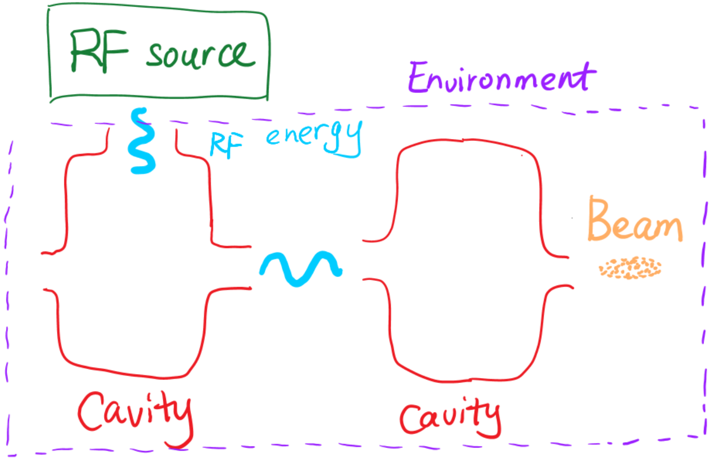
V. Dolgashev, *et al.*, APL 97, 171501 (2010).

Where can improvements happen?

RF sources:
- Improvements in RF sources
- Alternative source with structure wakefield acceleration

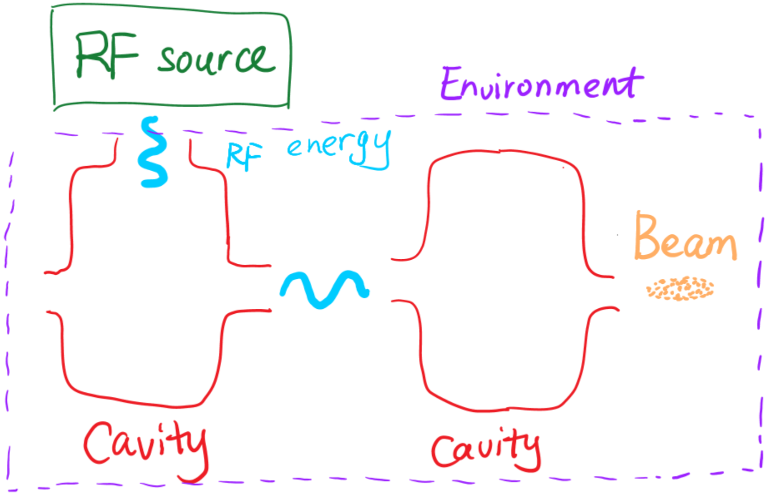
Environment:
- Cryogenic operation
- High magnetic field

Cavity properties:
- Geometry optimization
- Advanced structures
- Frequency
- Copper materials



Power coupling:
- RF couplers and windows
- Distributed coupling

Beam acceleration:
- High-order mode detuning and damping



Cavity properties:

- Geometry optimization
- Advanced structures
- Frequency
- Copper materials

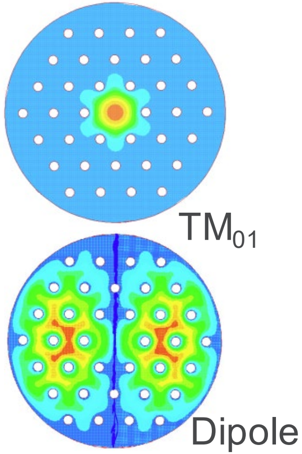
Cavity geometry

- General optimization goals for NCRF **accelerating** structures:
  - High “shunt impedance”
  - Low surface E/H field to gradient ratios
  - Minimum acceptable beam aperture
  - Higher-order modes (HOM) damping
  - …

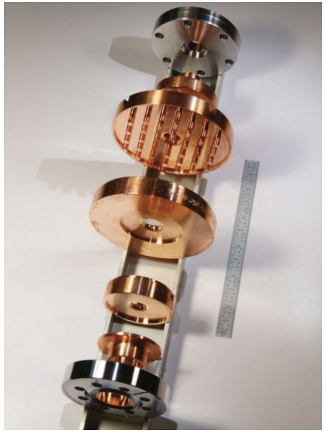
- NCRF structures for other purposes:
  - Transverse deflecting cavities for diagnostics
  - Crab cavities for colliders
  - Beam position monitor cavities
  - Storage cavities (e.g. recent spherical cavities)
  - RF kickers
  - …

Advanced RF structures

Photonic bandgap structures

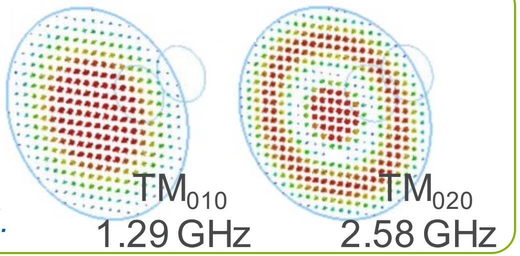


E. Smirnova *et al.*



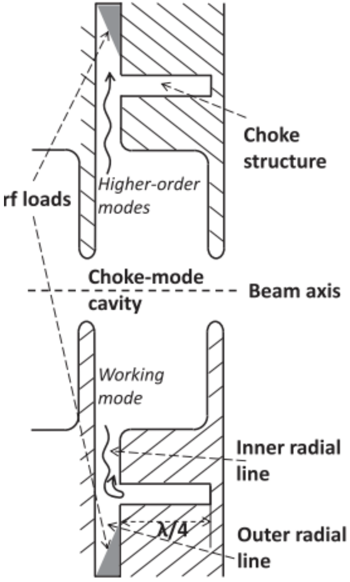
R. Marsh *et al.*

Bi-modal structures



H. Feng *et al.*

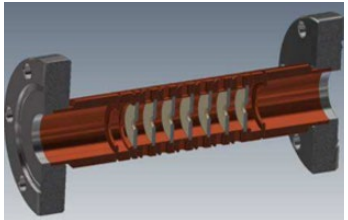
Choke-mode structures



H. Zha *et al.*

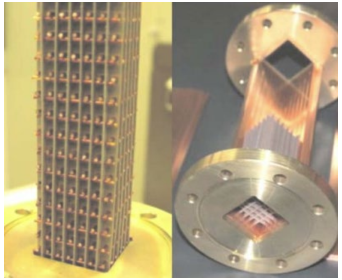
Dielectric structures

C. Jing *et al.*

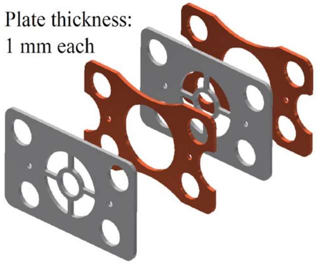


J. Shao *et al.*

Metamaterial structures



S. Antipov *et al.*

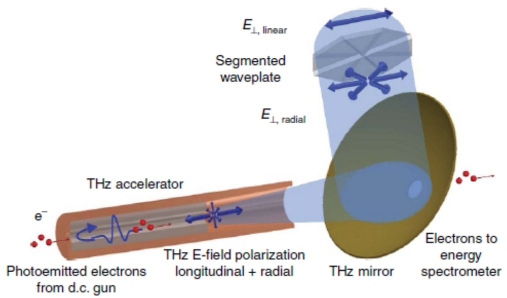


X. Lu, J. Picard, *et al.*

Sub-terahertz and terahertz acceleration

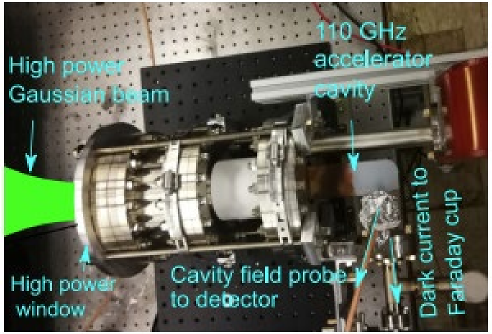
- Higher gradients from the frequency scaling of shunt impedance
- Key challenges:
  - Fabrication
  - Power sources

THz pulses



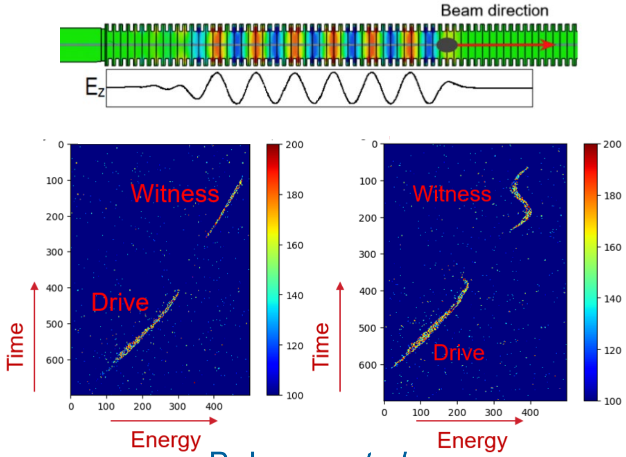
E. Nanni *et al.*

mm-wave RF sources



M. Othman *et al.*

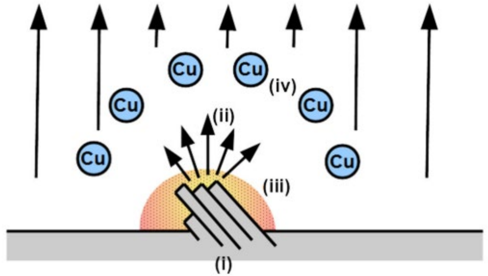
Electron beam



B. Leung *et al.*

Cavity materials: Hard copper and copper alloys

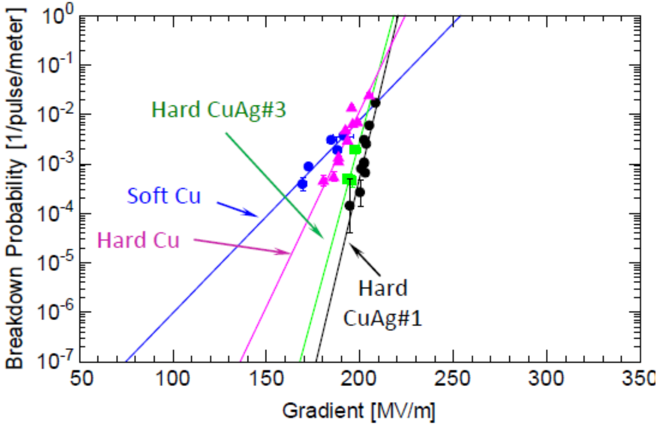
- **Hard** copper materials
  - **Harder** materials with **lower mobility** of crystal defects such as dislocations are expected to reduce RF breakdown

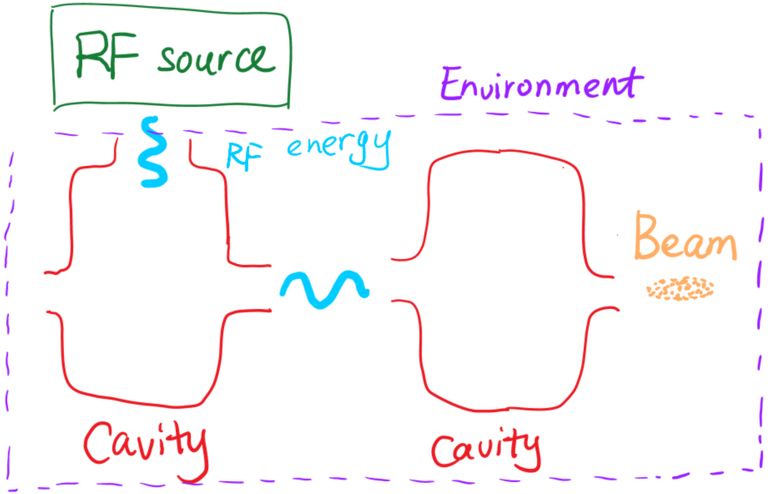


- Material design to study the trade-off between higher mechanical strengths (good) and lower electrical conductivity (bad) ← G. Wang, et al., APL 120, 134101 (2022)

- High-power testing of hard Cu, CuAg
  - New methods of building structures: e-beam welding, TIG welding, clamping, additive manufacturing

V.A. Dolgashev, "High gradient, X-band and above, metallic RF structures", EAAC 2015





Environment:

- Cryogenic operation
- High magnetic field

Cryogenic operation

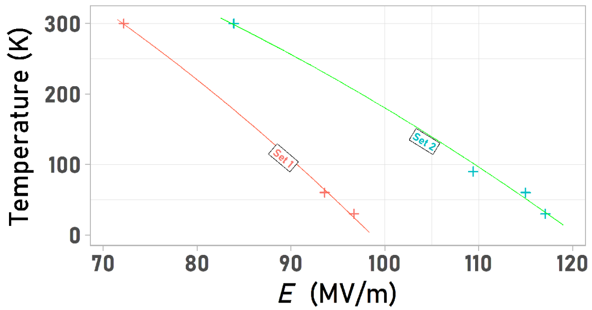
- Cooling copper cavities down
  - Higher breakdown resilience from lowering crystal defects mobility and thermal stress
  - Lower resistivity → higher quality factor

Theory

$$T = \frac{-E_f + \epsilon_0 \Delta V E^2}{k_b(\ln \mathrm{BDR} - \ln a)}$$

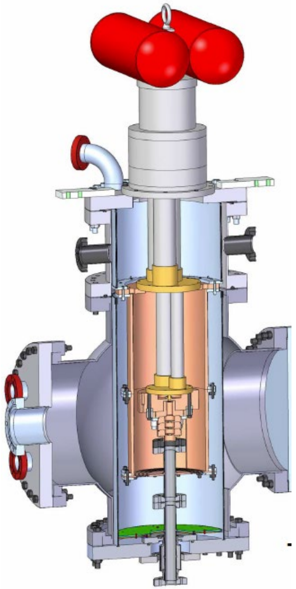
K. Nordlund and F. Djurabekova, PRSTAB 15, 071002 (2012).

Pulsed DC testing



M. Jacewicz *et al*., Phys. Rev. Appl. 14, 061002 (2020)

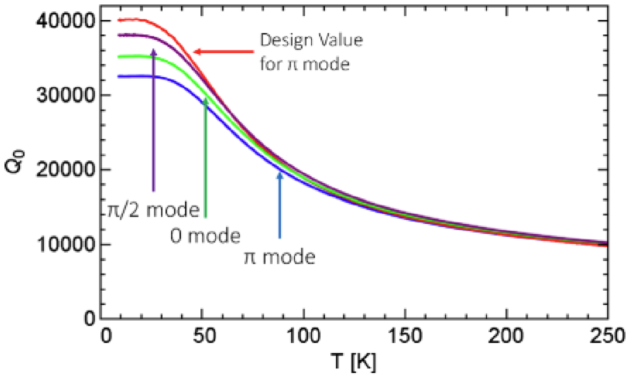
RF testing



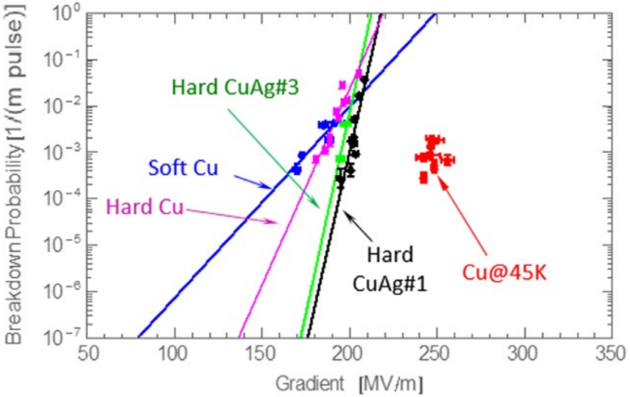
A. D. Cahill *et al*., PRAB 21, 102002 (2018)

Cryogenic NCRF structures testing

X-band copper structures at cryogenic temperatures



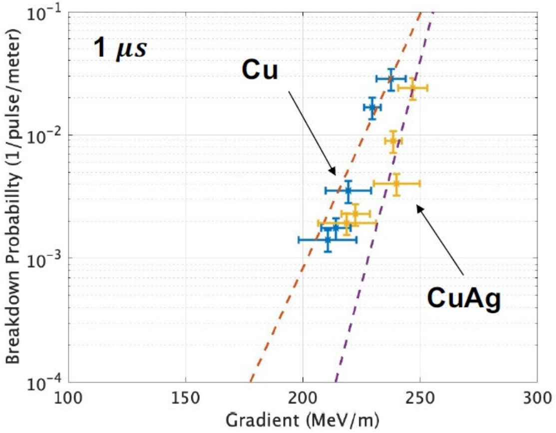
Cu@45 K outperformed others



A. D. Cahill *et al*., PRAB 21, 102002 (2018)

C-band copper structures tested at 77 K

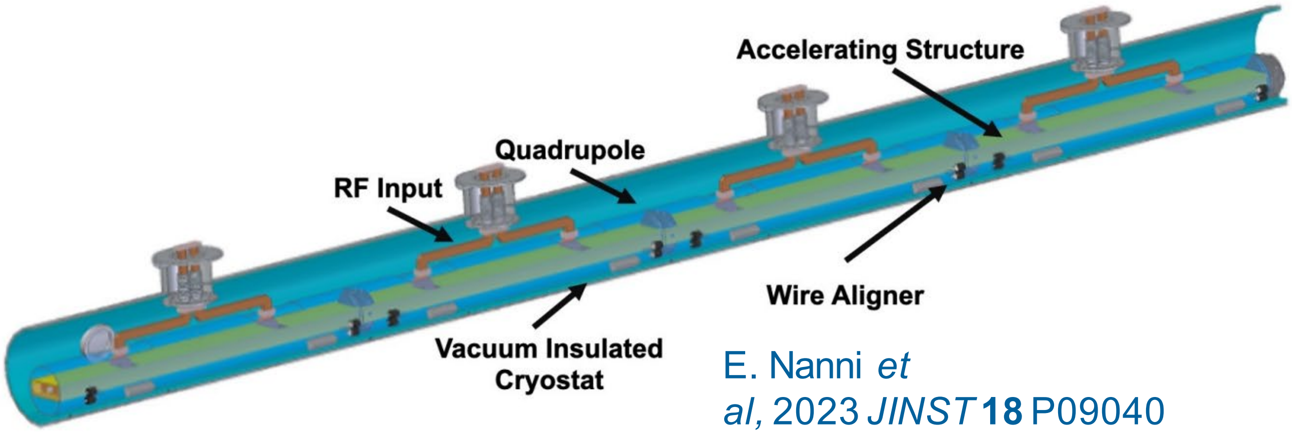
- Qualify factor improved by 2.5 X for Cu and 2.9X for CuAg from cold test
- High-power test



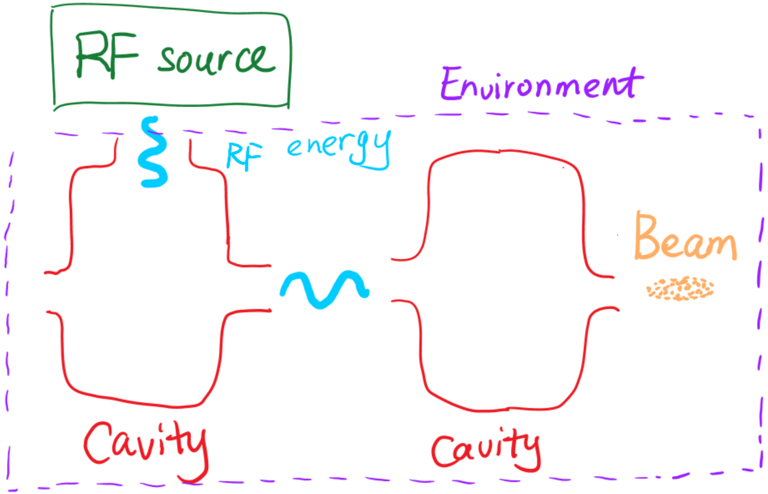
E. Nanni, "Cold Copper High Gradient Single-Cell Structure Tests", LCWS, July 2024

Corresponding collider proposal

- **Cool copper collider (C[3])**
  - Cryogenic copper accelerators, C-band, liquid nitrogen
  - 8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m



E. Nanni *et al*, 2023 *JINST* **18** P09040

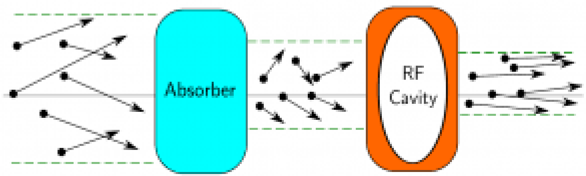


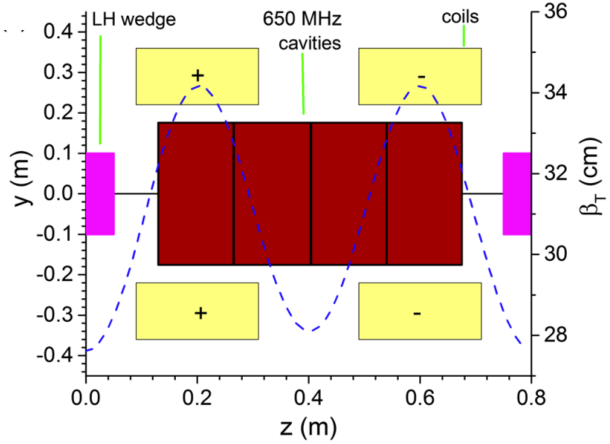
Environment:

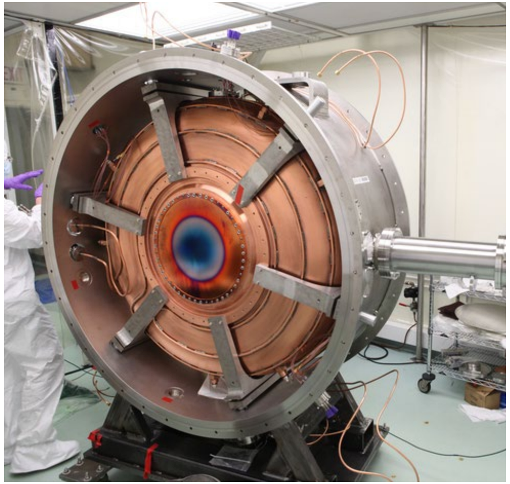
- Cryogenic operation
- High magnetic field

RF cavities in strong magnetic field

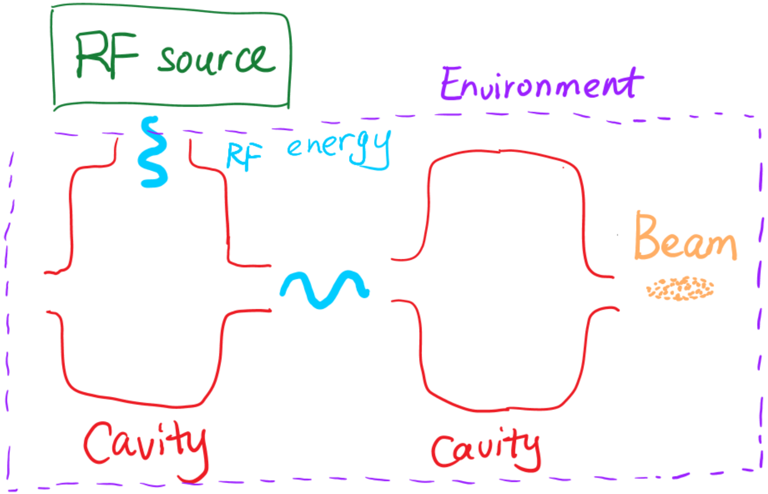
- NCRF cavities in a strong solenoid magnet **muon ionization cooling**, a key technology towards the **Muon Collider**
  - Key characteristics of muons:
    - elementary particles
    - $m_\mu = 207 m_e$
    - lifetime = 2.2 μs







D. Stratakis and R. Palmer Phys. Rev. ST Accel. Beams 18, 031003 (2015);
MICE collaboration. Nature 578, 53–59 (2020).

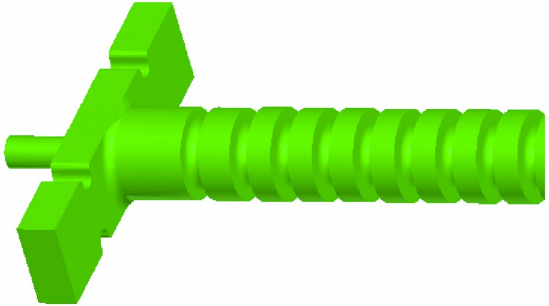


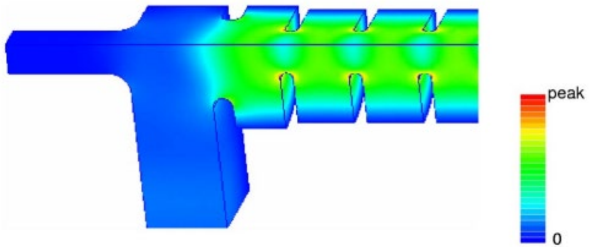
Power coupling:

- RF couplers and windows
- Distributed coupling

RF couplers and windows

TM$_{01}$ mode-launcher **coupler**

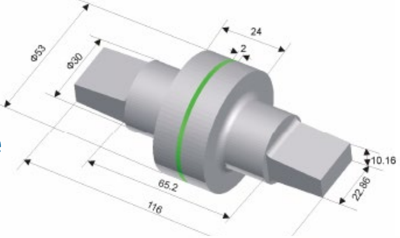




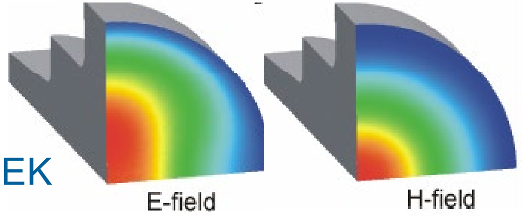
C. Nantista *et al*., PRSTAB 7, 072001 (2004)

RF **windows**

- Coax or waveguide
- Ceramic materials
- Coating
- RF design to lower electric field
- Thermal stress management



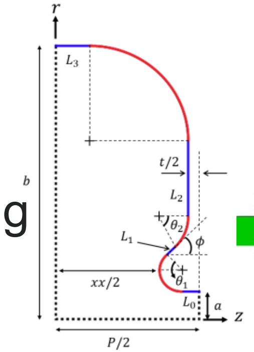
Traveling-wave windows

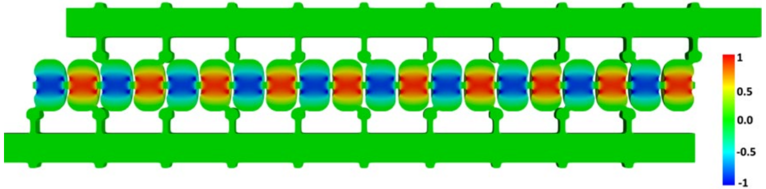


S. Kazakov, KEK preprint, 1998

Distributed coupling linacs

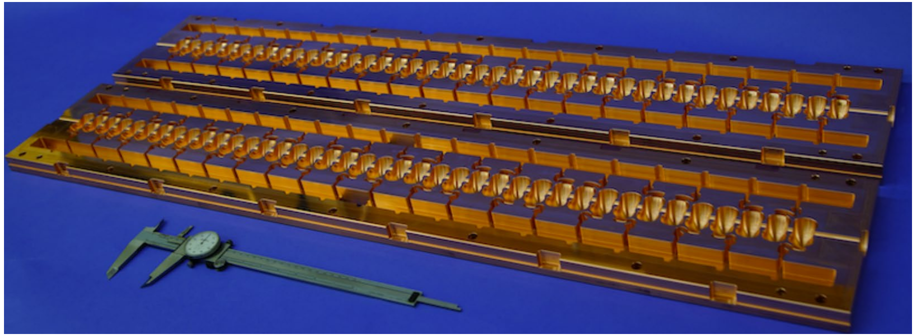
- An invention that enables a new linac topology
  - Fully optimized cavity shapes by removing the constraint on coupling between cells
  - Inexpensive fabrication

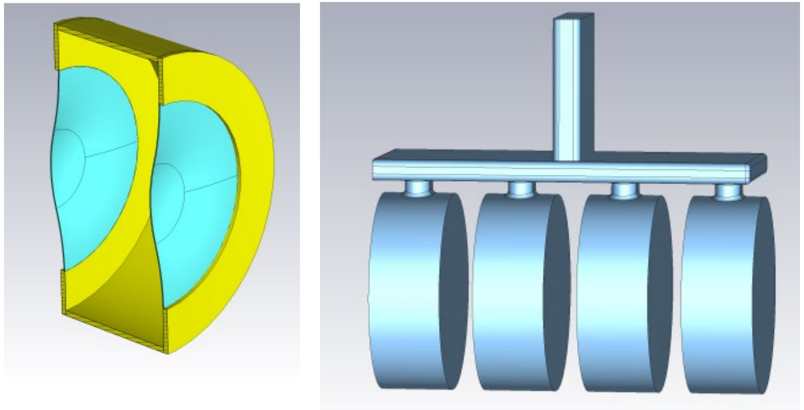




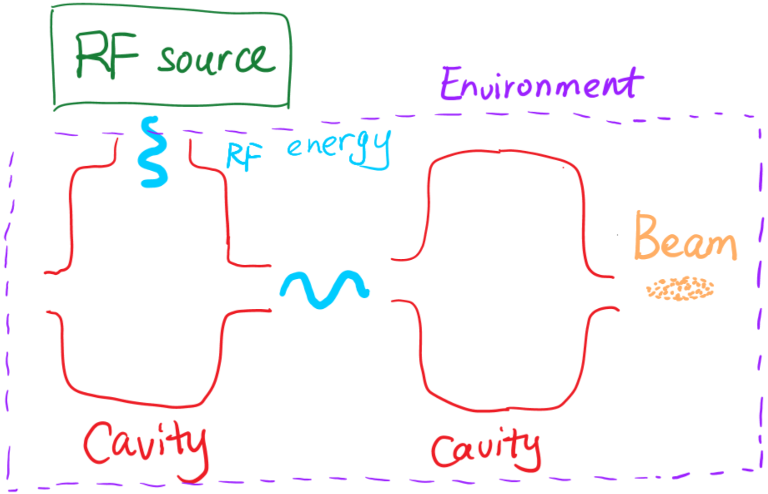
S. Tantawi *et al*., PRAB 23, 092001 (2020)

- Applied in C^3 baseline design, also being investigated for muon cooling





T. Luo *et al*, IPAC 2024.



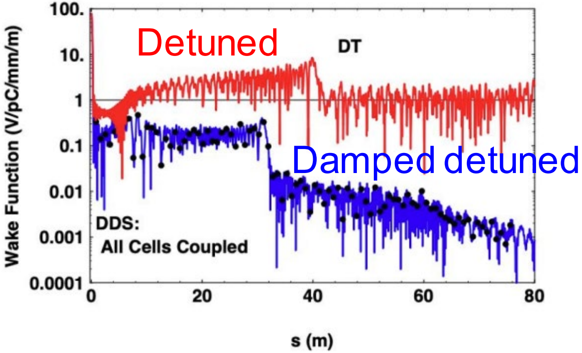
Beam acceleration:

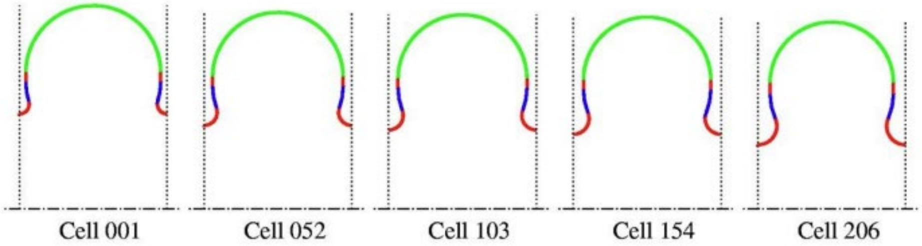
- Higher-order mode detuning and damping

Higher-order modes detuning and damping

For NLC/JLC

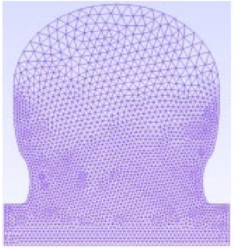
Round Damped Detuned Structure (RDDS)

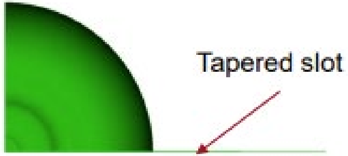


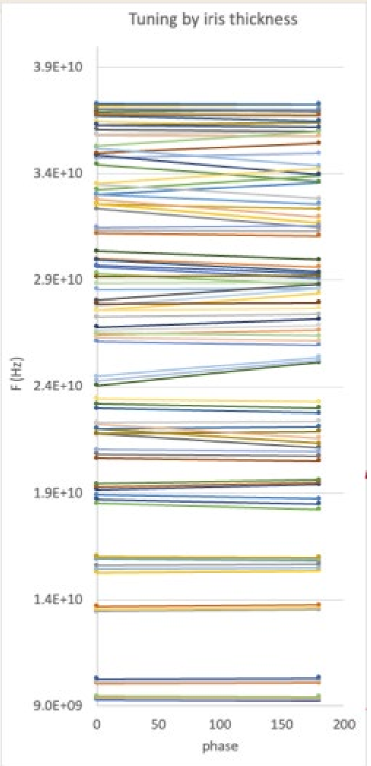


Z. Li *et al.*, PAC 1999

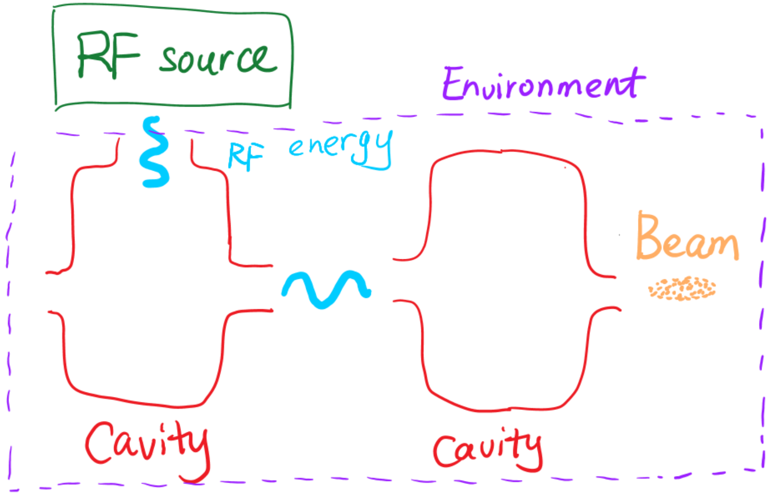
For C^3







Z. Li, "HOM Detuning and Damping of C-Band Distributed Coupling Structure", LCWS, July 2024



<u>RF sources:</u>

- RF sources (compact, low cost/voltage, high efficiency)
- Alternative sources with structure wakefield acceleration

Improvements in RF sources

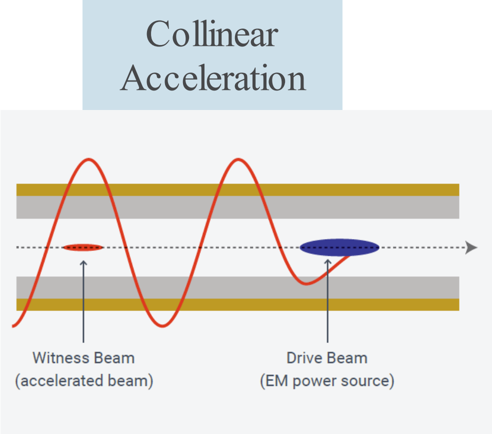
- Solid-state amplifiers (especially at low frequencies)
- Compact, low-cost and low-voltage **klystrons**
- Auxiliary RF components: power combiners, pulse compressors, power distribution networks, circulators, (RF windows), …

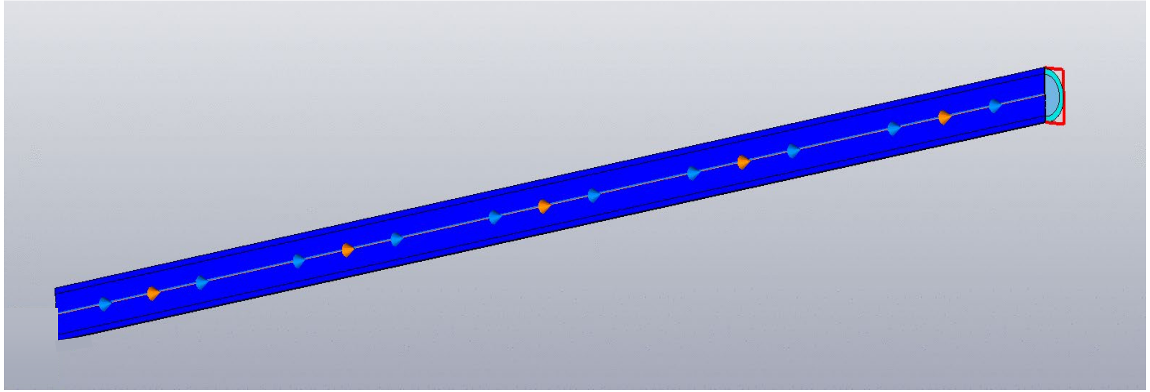
X-Band Multi-Beam Klystron @SLAC

352 MHz solid-state amplifier modules @ APS

Structure wakefield acceleration (SWFA)

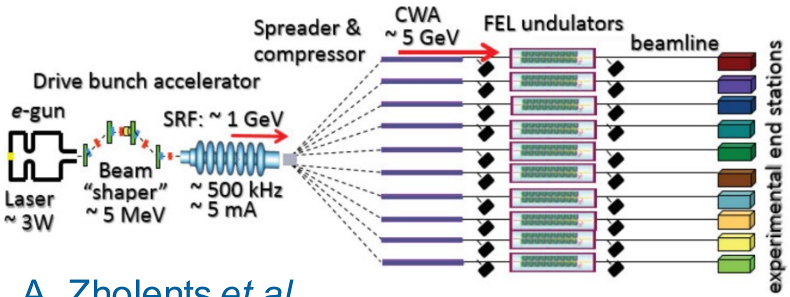
- Driven by short ultrarelativistic electron bunches
  - Beam-driven wakefield acceleration (one advanced accelerator concept)
  - Extract wakefield from a “drive” beam to accelerate a “witness” beam





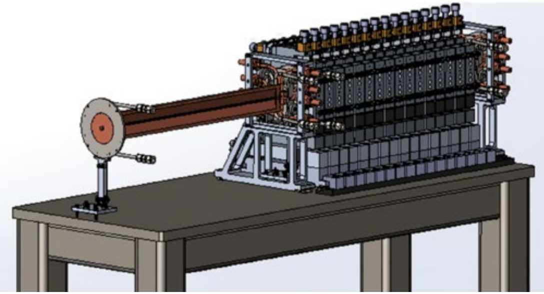
Collinear wakefield accelerator (CWA) R&D

- An application being developed at ANL
  - A compact multi-user XFEL
  - CWA in 180 GHz corrugated waveguides
- Advantages:
  - Compact, high efficiency, high rep rate
- Addressing key challenges:
  - Beam breakup instabilities
  - Thermal loading and HOM

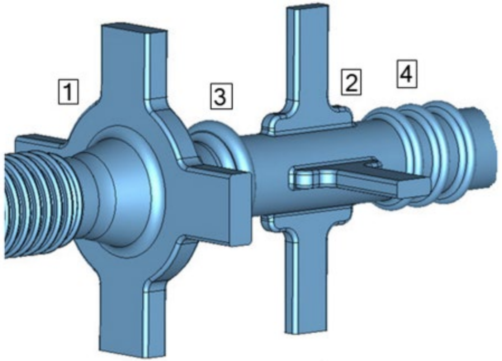


A. Zholents *et al.*

Solution: Strong permanent magnet

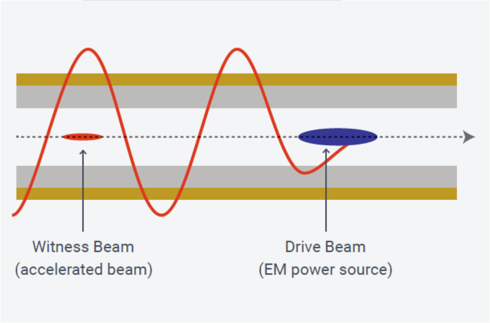


Solution: Transition section to remove unused energy and to extract HOM

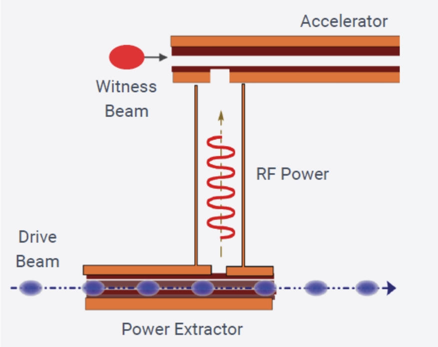


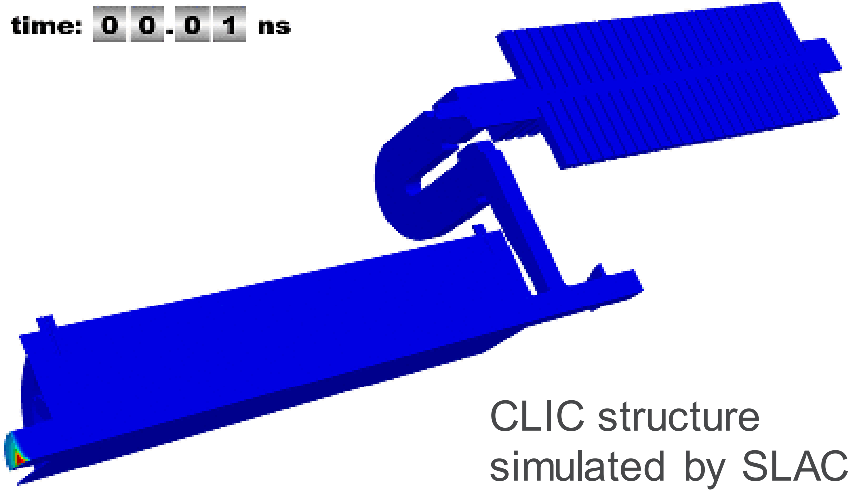
Two-beam acceleration (TBA)

Collinear Acceleration



Two-Beam Acceleration



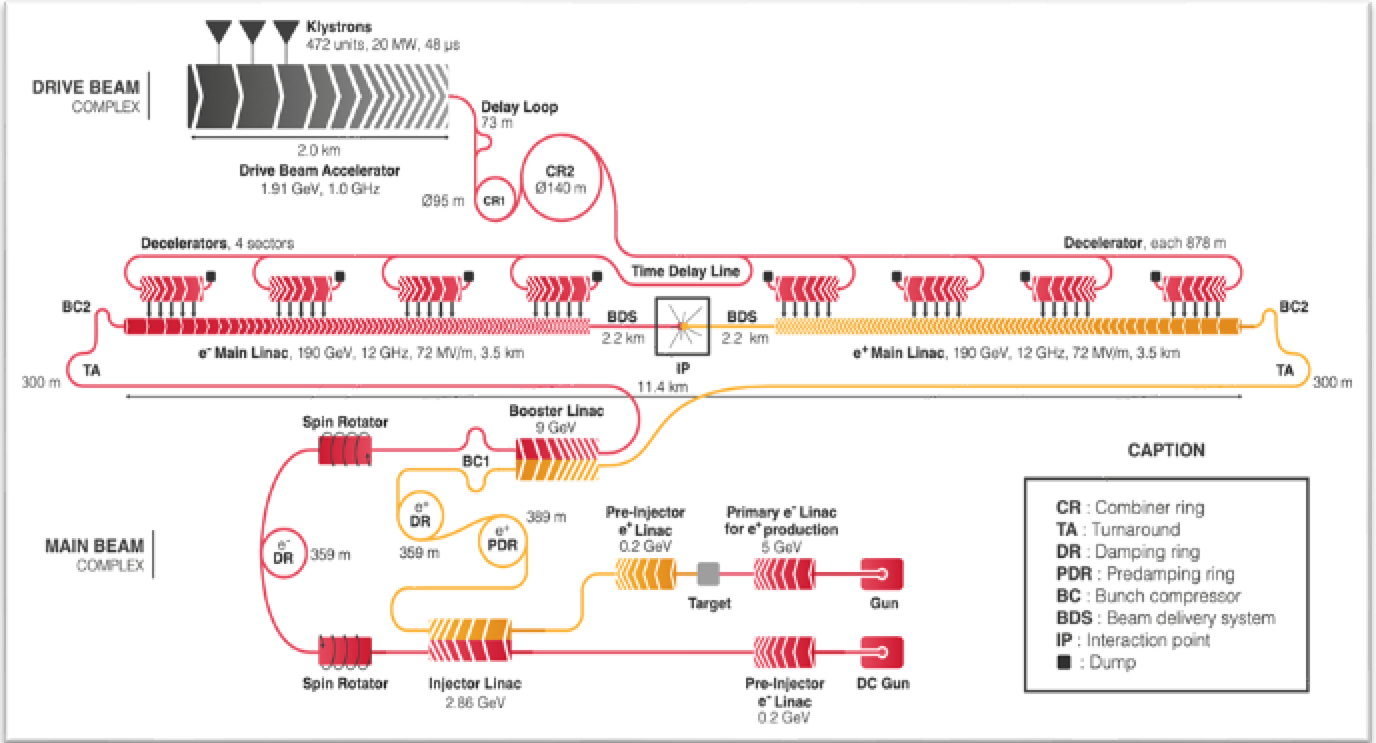


CLIC structure simulated by SLAC

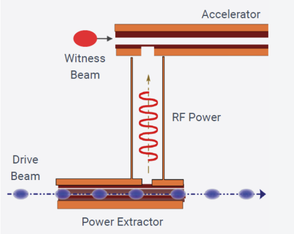
- Two-beam acceleration (TBA) is a more mature technology for a linear collider
  - **Compact Linear Collider (CLIC)** CDR
  - Recent high-gradient demonstration at the **Argonne Wakefield Accelerator (AWA)** by using short-pulse acceleration (a few nanoseconds)

Compact LInear Collider (CLIC)

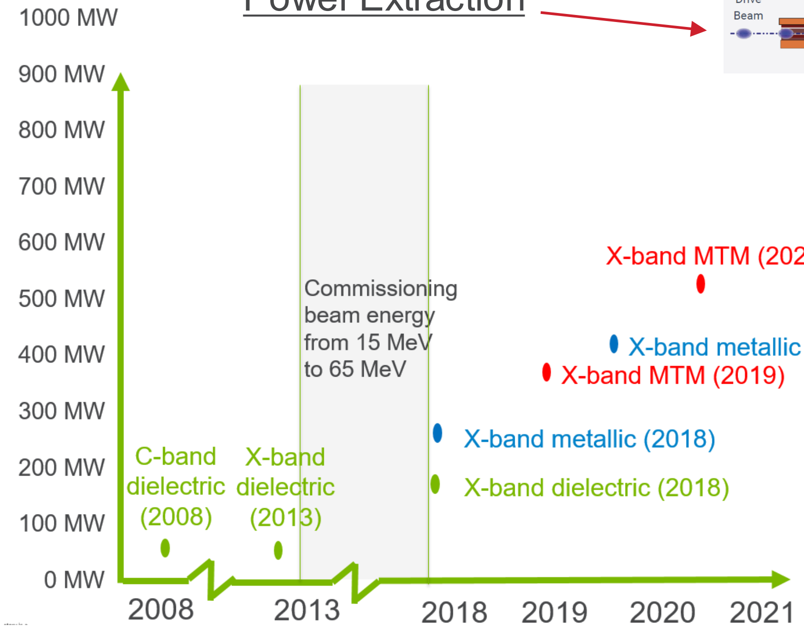
- NCRF 12 GHz at 72 MV/m with two-beam scheme (drive beam at 1 GHz), with a pulse length of 244 ns



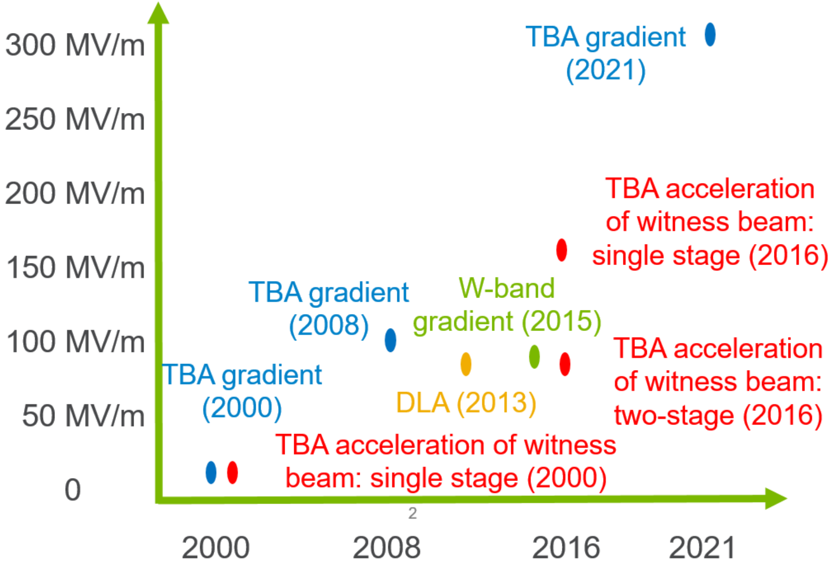
Progress in two-beam acceleration at AWA



Power Extraction

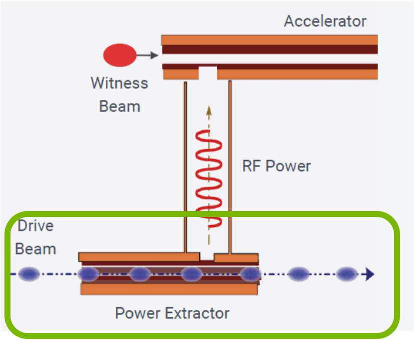


Acceleration Gradient

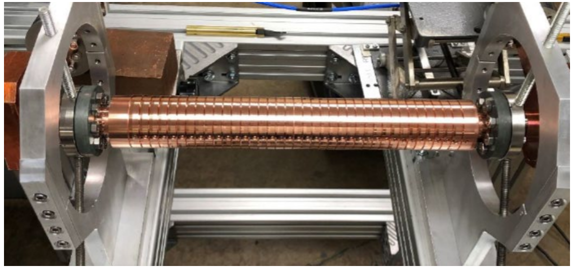


www.anl.gov/awa/virtual-tours

Unique SWFA-based short-pulse RF source

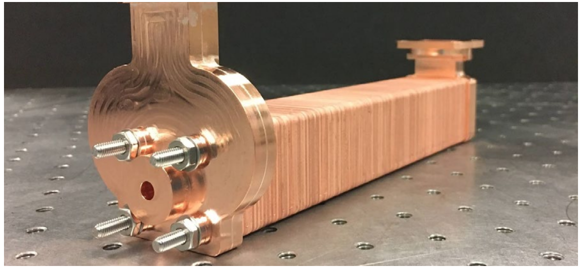


Metallic disk-loaded, 400 MW, 6 ns FWHM



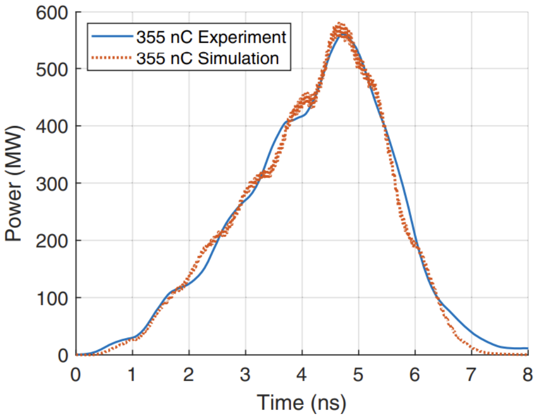
M. Peng *et al*, IPAC 2019, MOPRB069

Metamaterial, 565 MW, 6 ns FWHM



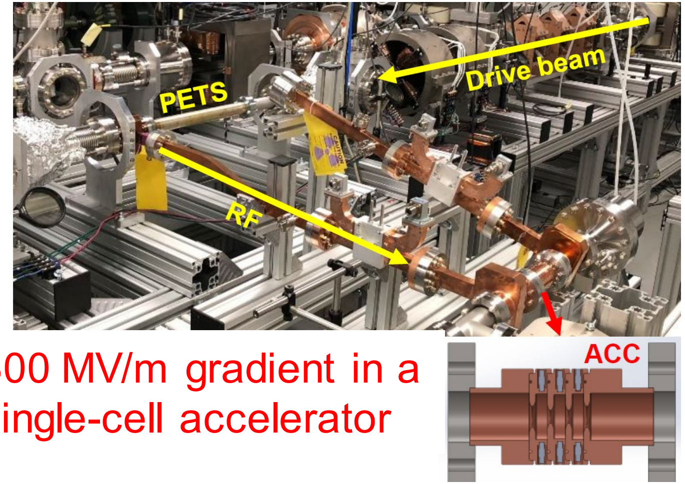
J. Picard *et al*, PRAB **25**, 051301 (2022)

- SWFA power extractors as short-pulse RF sources
  - New operation regime of accelerators
  - Enabled by the high-charge bunch trains at AWA

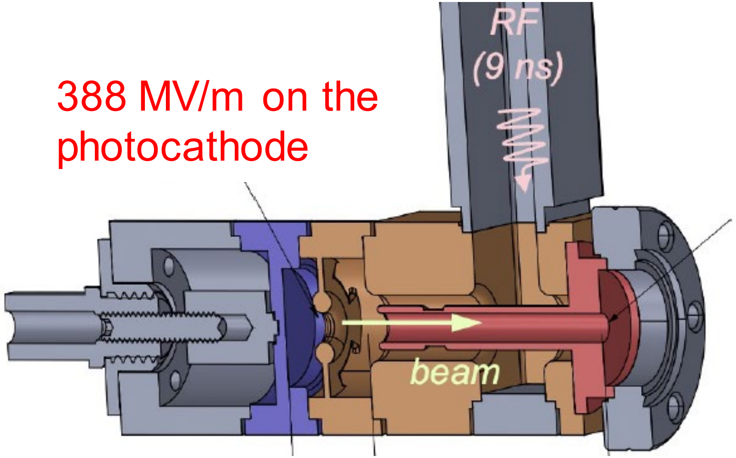


Short-pulse operation: path to high gradient

- Close to **400 MV/m** measured on an X-band photocathode surface
- Breakdown insensitive acceleration regime
  - Empirical scaling law: Breakdown rate $(\mathrm{BDR}) \propto E^{30}\tau^{5}$
  - Reduces pulsed heating, multipacting; little time for plasma expansion
- **To be demonstrated**: high-brightness beam generation, high-quality beam acceleration (e.g. impact of beam loading)



300 MV/m gradient in a single-cell accelerator

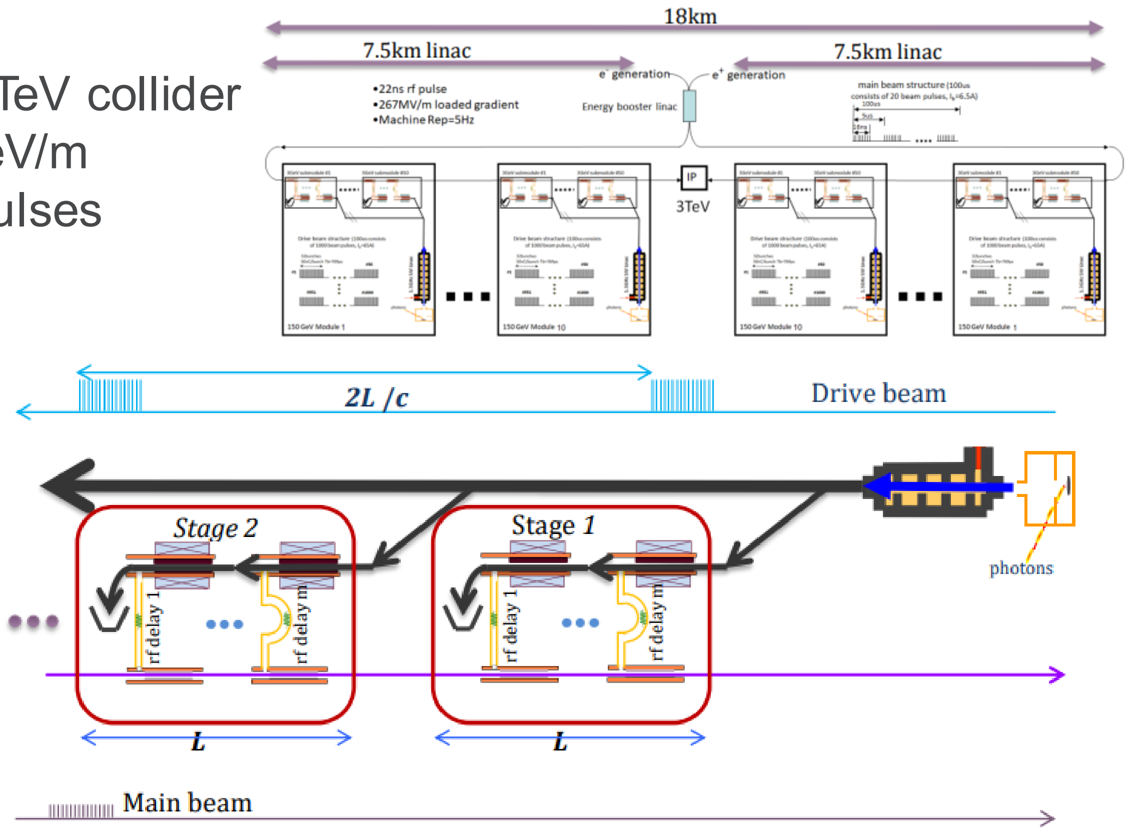


388 MV/m on the photocathode

Short-pulse SWFA-based linear collider

Argonne Flexible Linear Collider (AFLC)

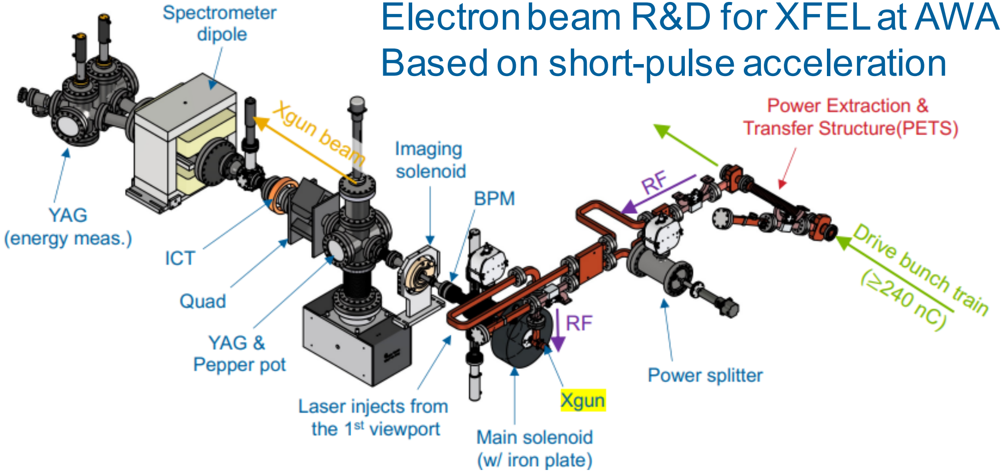
Conceptual 3 TeV collider
267 MeV/m
20 ns pulses



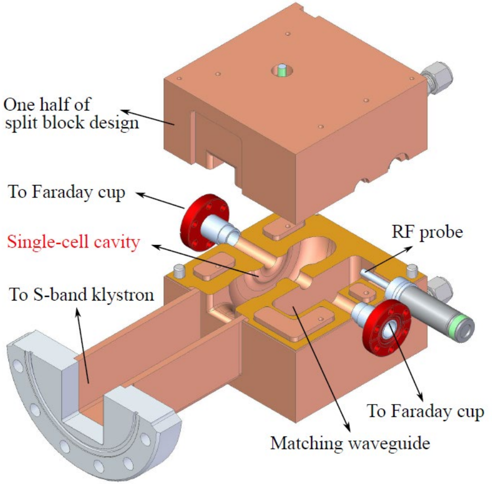
Nearer-term: light sources, medical applications, …

- A good-quality beam is quite useful, in:
  - Driving a free electron laser:
    - Ultra-Compact XFEL (UC-XFEL), cryogenic operation
    - Compact XFEL demo at AWA, two-beam acceleration
  - Medical accelerators with compact linacs

Electron beam R&D for XFEL at AWA
Based on short-pulse acceleration



RF energy modulator for proton therapy



X. Lu *et al*, RSI 92, 024705 (2021)

Conclusions

- NCRF accelerators are critical in many applications, including future colliders.
- Numerous exciting concepts have emerged in recent years.
- Continuous R&D will be rewarding.
- My personal views:
  - **Invest in innovative ideas:** Transformation of brilliant concepts into various applications with remarkable performance improvement
  - **Learn from the past:** Especially in the planning of large-scale projects
  - **The science is fun after all:** The decades-long mystery of fundamental RF breakdown physics is inherently multidisciplinary, and input from other communities would be valuable.
  - **We need more people:** "There is a shortage of engineers and scientists trained to work in high-power RF." – 2017 DOE RF Accelerator R&D Strategy Report