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NORMAL-CONDUCTING RF FOR BES ACCELERATORS

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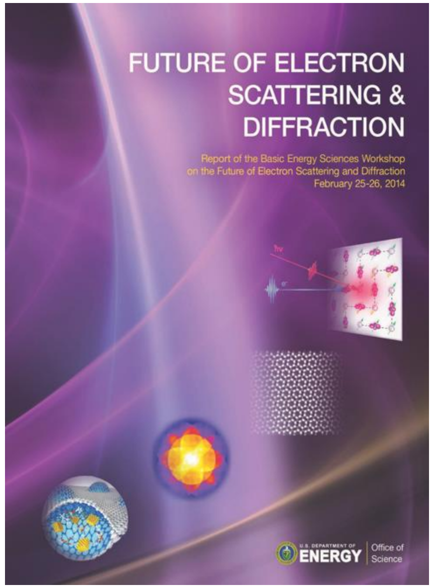
Picture credit: BRN on accelerator-based instrumentation (BES)

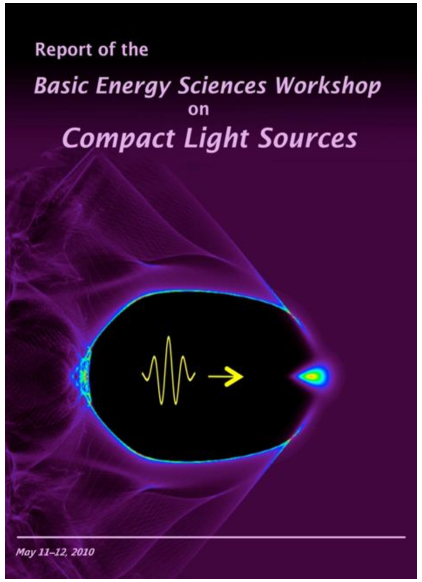
BACKGROUND

Relevant BES Round Tables and Basic Research Need (BRN) Workshops (non exhaustive list)

https://science.osti.gov/-/media/bes/pdf/reports/files/Future_of_Electron_Scattering.pdf



https://doi.org/10.2172/1616511



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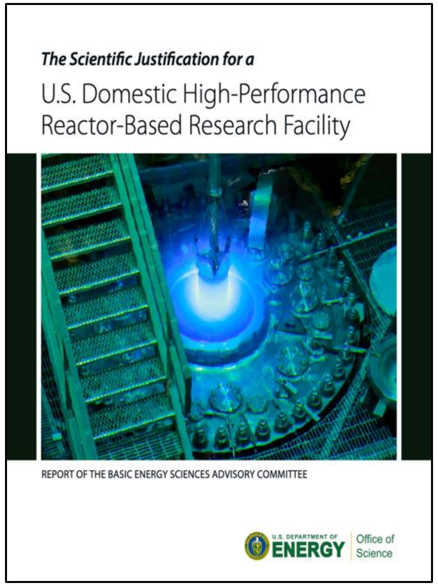


https://science.osti.gov/-/media/bes/besac/pdf/Reports/US_Domestic_High-Performance_Reactor-Based_Research_Facility.pdf

https://science.osti.gov/-/media/bes/pdf/brochures/2024/24-G00737-BRN-ABI-brochure-Final.pdf

INTRODUCTION (I)

BRN on accelerator-based instrumentation outcomes

- **Achieve Theoretical Performance Limits:** Advance high-power electronics, lasers, optics, detectors, and diagnostics towards physical and technological limits to maximize accelerator performance.
- **Beam Generation Fundamentals:** Research the fundamentals of beam generation and probe parameters' behavior to achieve max performances.
- **Develop Advanced Beam Manipulation:** Create methods and techniques to manipulate and multiplex beams with unprecedented precision and speed, improving beam quality and tunability for complex experiments.
- **Advance Accelerator Materials and Fabrication:** Develop new materials with controllable properties and advanced fabrication processes for particle sources, optics, and accelerator components.
- **Optimize Component Integration:** Couple precision design of complex accelerator components with modeling and optimization to create new paradigms for fabrication and integration.
- **Understand Performance-Limiting Mechanisms:** Identify and analyze key phenomena that hinder transformative changes in accelerator-based facility capabilities.

https://science.osti.gov/-/media/bes/pdf/brochures/2024/24-G00737-BRN-ABI-brochure-Final.pdf

INTRODUCTION (II)

NCRF as an enabling technology for BES applications

- **Use of NCRF in BES accelerators:**

ACCELERATION	BEAM FORMATION	MANIPULATION & DIAGNOSTICS
NCRF is pivotal for achieving high-gradient and high-duty cycle acceleration, enabling compact accelerator designs.	NCRF is essential for the generation and formation of charged-particle beams, including electron and proton beams, for BES applications.	NCRF is increasingly utilized in the emerging field of phase-space tailoring and for precise beam diagnostics

- **Basic Energy Science applications:**
  - Currently includes X-ray and neutron scattering facilities (six national facilities: ALS@LBNL, APS@ANL, LCLS, NSLSII@BNL, SSRF@SLAC, SNS@ONRL)
  - Mid-scale facilities electron scattering (pushing toward ultrafast imaging or diffraction)
  - Contemplated next generation facilities: BESAC's green-field FEL, new capabilities at existing facilities

ACCELERATION (I)

High-gradient acceleration large aperture for direct injection in SRs

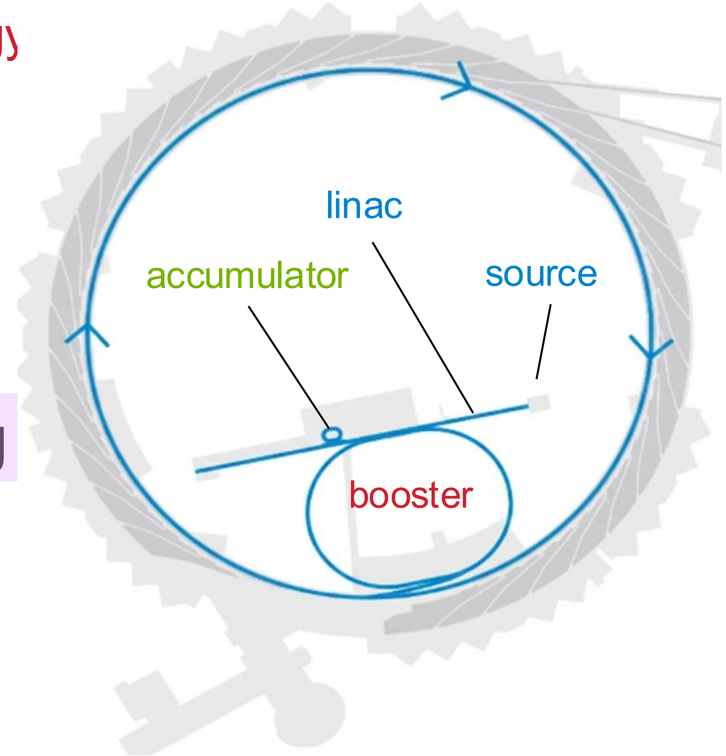
- Current **storage-ring (SR)** designs rely on staged injector chain:

source + linac ➡ **accumulator ring** ➡ **booster ring** ➡ **storage ring**

source + linac: acceleration of moderate-charge bunches to ~100’s MeV

accumulator ring: high-charge bunch formation

booster ring: acceleration to final SR energy



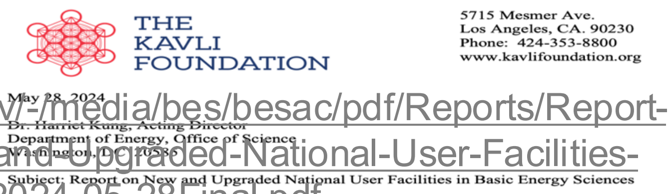
- Attaining higher stored current in SRs would benefit from direct injection (e.g., work at EBS@ESRF)
  - — $f_{rep} \sim \mathcal{O}(10)$ Hz
  - — Typical SR injection energies $\mathcal{O}(5)$ GeV
    - ➡ high-gradient, large aperture (high-charge)

source + linac ➡ storage ring

source + linac: acceleration of high-charge bunches to final SR energy

ACCELERATION (II)

High-gradient acceleration manipulation for FLS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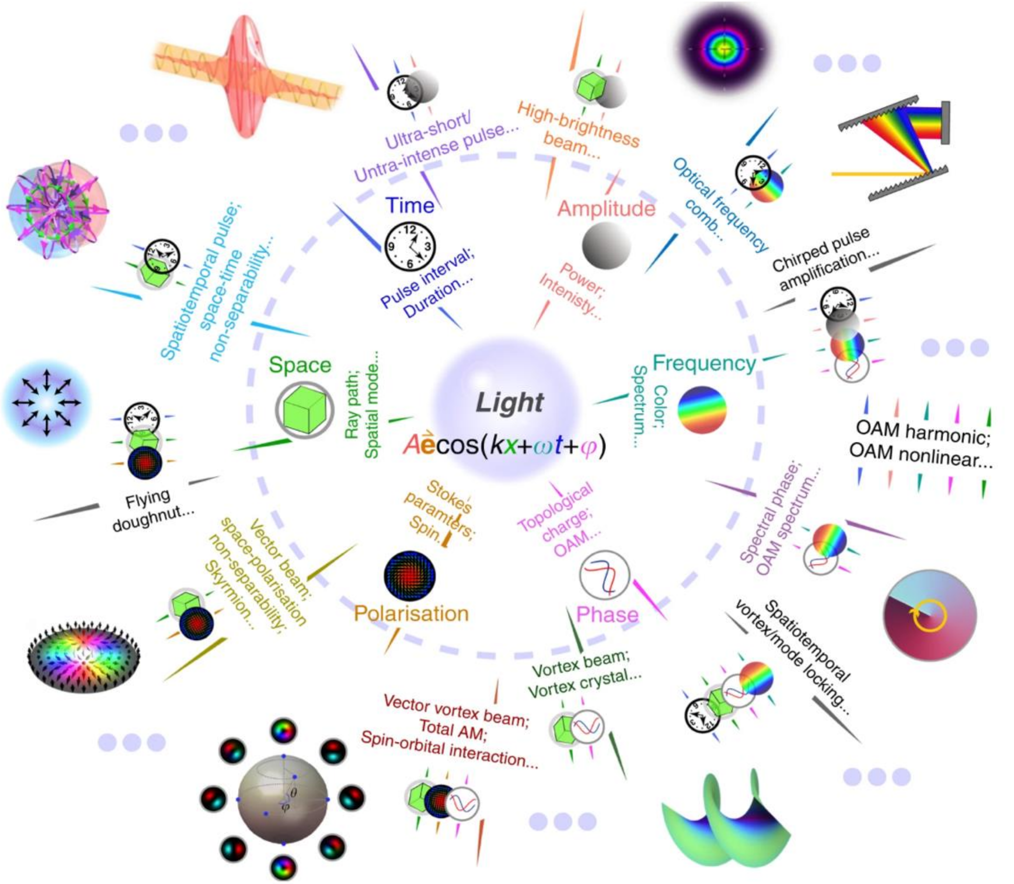
May 28, 2024
Dr. Harriet Kung, Acting Director
Department of Energy, Office of Science
Washington, DC 20585
Subject: Report on New and Upgraded National User Facilities in Basic Energy Sciences

https://science.osti.gov/-/media/bes/besac/pdf/Reports/Report-to-BESAC-on-New-and-Upgraded-National-User-Facilities-2024-05-28Final.pdf

- Basic Energy Science Advisory Committee (BESAC) report of May 2024 recommends: “Future Light Source (FLS) – a ‘green field’ light source, location(s) TBD”
- Several concepts under exploration for FLS: a possible NCRF-related option is based on a *compact* (~ $\mathcal{O}(100)$ m) versatile FEL based on high-gradient acceleration
  - — bright *e*- bunches ~100 pC
  - — High-repetition rate $\mathcal{O}(1)$kHz
    ➡ multiplexed user beamline
  - — Attain tender to hard X rays
  - — “structured” photon-pulse capabilities



https://doi.org/10.1038/s41377-022-00897-3

BEAM FORMATION (I): ELECTRONS

Bright electron beams for FEL & ultrafast electron scattering systems

- **Increasing Brightness:** Achieving higher surface electric fields on the cathode generally improves beam brightness.
- **Critical Role of Final Energy**: Final beam energy plays a crucial role in “freezing” the longitudinal beam dynamics and mitigating space charge effects
  ➡ split versus integrated injector designs.
- **Development of Robust NCRF Guns**: Focus on developing robust and reliable NCRF guns with high stability (ultra-low energy jitter for UES).
- **Extended Cathode Lifetime**: Low-MTE photocathodes typically require maintaining pristine UHV (10^{-10} Tor) conditions to prevent degradation
  ➡ frequency choice

4D brightness
(ideally invariant)

E-field at the
cathode surface

$$\mathcal{B} \propto \frac{E^{\nu}}{MTE}$$

Mean-transverse energy
(material properties)

BEAM FORMATION (II): ELECTRONS

High-charge or high-Current electron beams

- **Higher-Current electron beams** for high-repetition rate FELs (e.g. LCLSX) and UED
  - Sub-GHz technologies (LBNL)
  - Adopted for LCLS-II, UED (HiRES), Shanghai and Shenzen facilities
  - Limited field on cathode <40 MV/m
  - Demonstrated reliable operation of semiconductor photocathodes
  - Simpler than SRF guns
  - R&D toward higher field needed
    ➡ path to higher brightness + simplified bunching scheme
- **Higher-Charge electron beams** for (i) direct injection in SR, and (ii) high-peak power (GW) generation for high-frequency structures
  - Currently based on GHz RF gun (AWA/CLIC)
  - Reliability, rather than high beam quality, is critical these systems operate at low repetition rates (1 Hz)

Synergy with HEP:
Muon collider – ionization cooling require low-frequency cavities with high field (ideally)

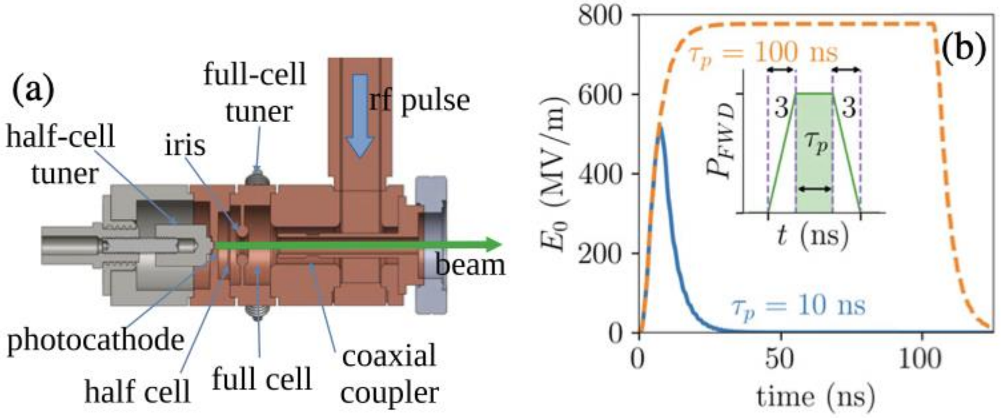
Synergy with NP:
EIC – high-charge bunch generation and acceleration for electron cooling

TECHNOLOGIES FOR ELECTRONS GENERATION & ACCELERATION (I)

Bright electron beams for FEL & ultrafast electron-scattering systems

GUNS W/ SHORT-RF PULSES

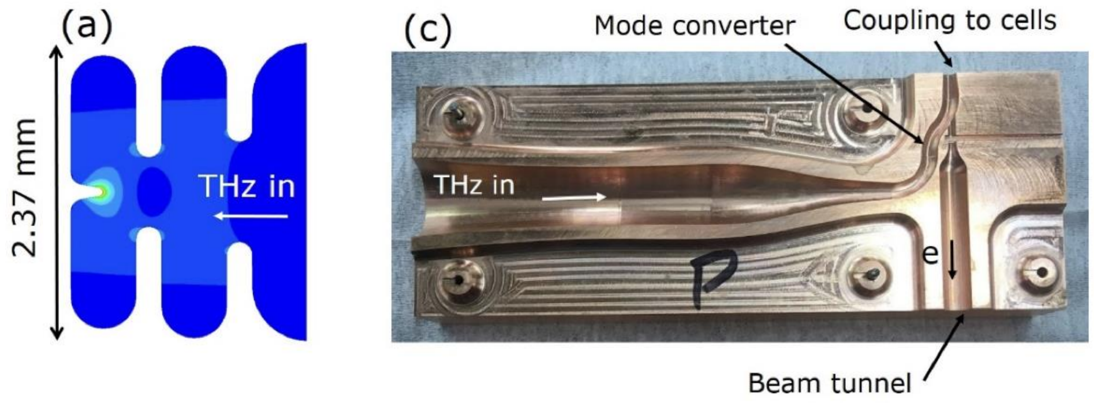
- Several project based on X-band guns beam-driven and klystron-based)
- Experimentally achieved ~400 MV/m on cathode



https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.25.083402

"QUASI-OPTICAL" STRUCTURES

- High E-field using sub-THz frequencies (metals, dielectrics)
- Small aperture ➡ limited charge but OK for UED/M



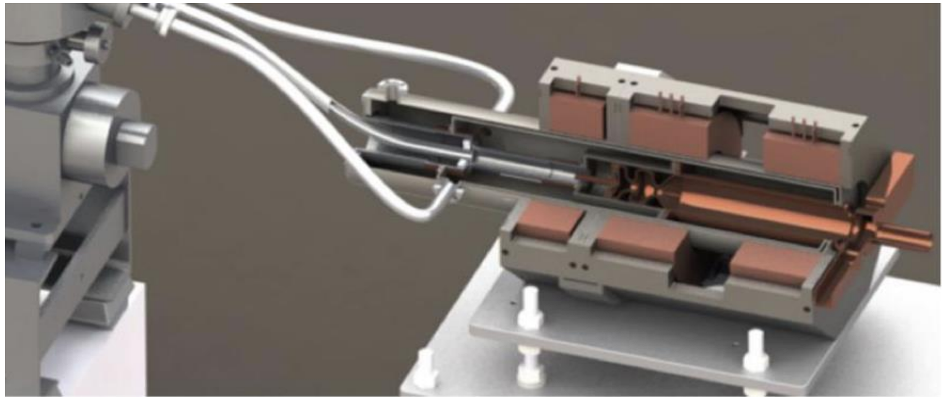
https://www.irmmw-thz.org/wp-content/uploads/2020/11/pid6452933.pdf

TECHNOLOGIES FOR ELECTRONS GENERATION & ACCELERATION (II)

Bright electron beams for FEL & ultrafast electron-scattering systems

CRYO-COOLED STRUCTURES

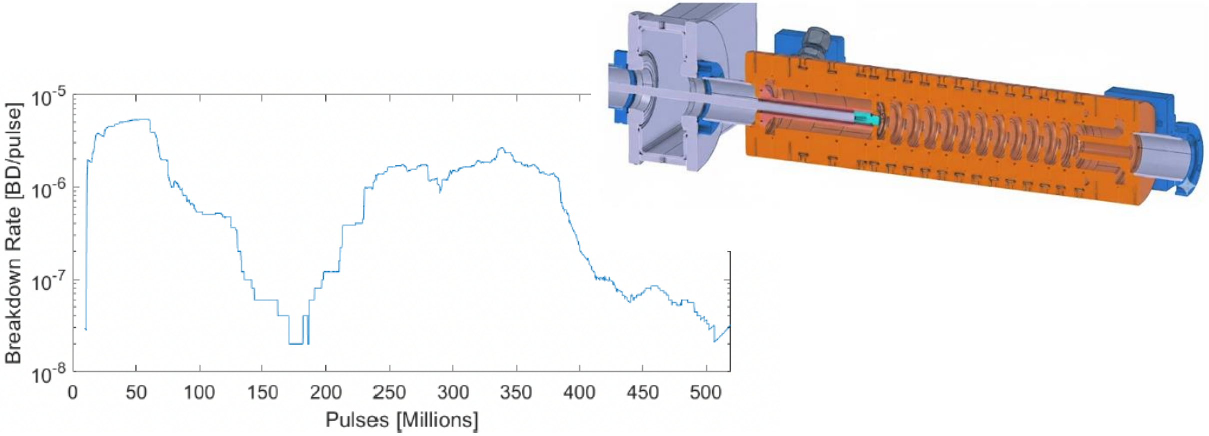
- Cryogenically-cooled (77 K) structures mitigate breakdown
- C- and S-band structures built
- C-band gun being tested at UCLA



https://doi.org/10.1103/PhysRevAccelBeams.22.023403

HIGH-FREQUENCY STRUCTURES

- Example of C-band klystron-power 1.5-cell TW RF gun for SwissFEL@PSI (PSI/INFN)
- So far 160 MV/m on cathode (50-200 ns pulses)

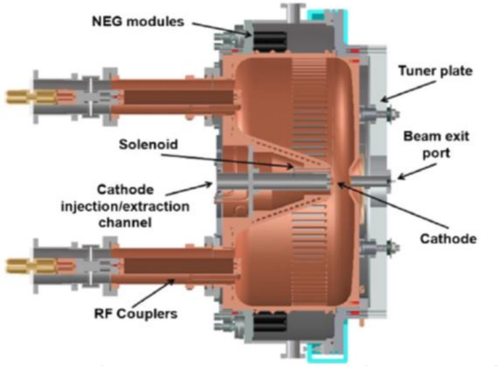


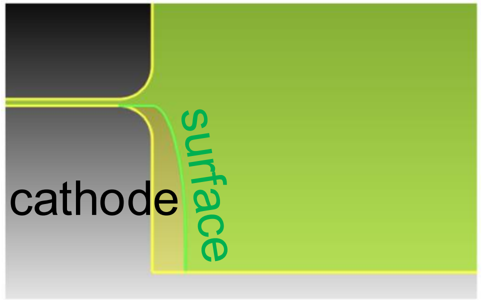
10.18429/JACoW-IPAC2024-WEPC69

TECHNOLOGIES FOR ELECTRONS GENERATION & ACCELERATION (III)

Bright electron beams for FEL & ultrafast electron-scattering systems

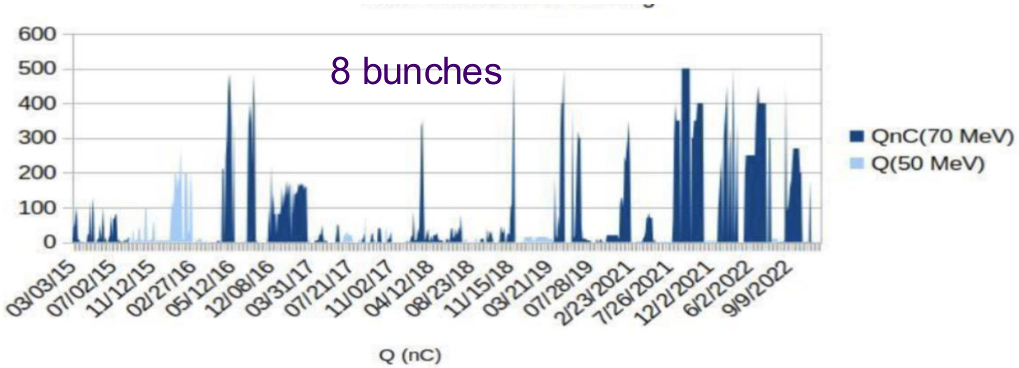
- **Higher-Current electron beams:** for high-repetition rate FELs (e.g. LCLSX) and UED
  - Designs follow LBNL VHF gun (~200 MHz),
  - CW operation at the cost of E field (limited to ~40 MV/m on cathode)
  - Low exit energy < 1 MeV ➡ limit bunch charge< 1nC
  - Significant pumping ➡ enables operation of high-QE/low-MTE photocathode
  - Work on improving dark-current emission





Communication from J. Qing & T. Luo

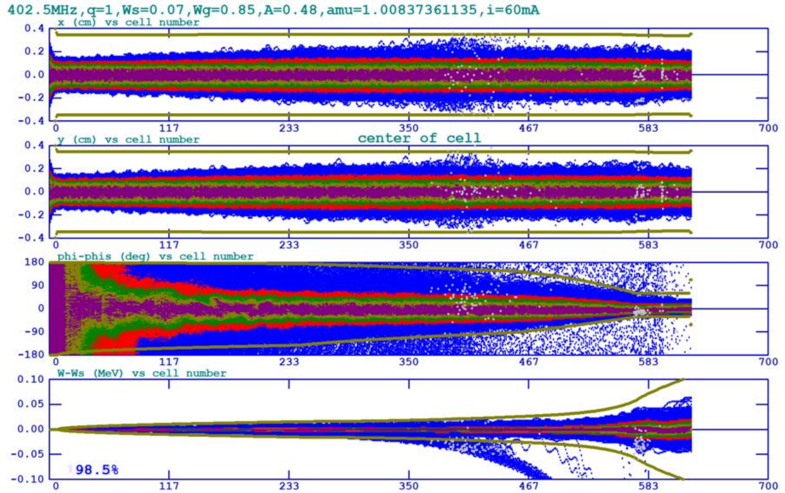
- **High bunch-charge generation:** for direct injection and high-peak-power generation
  - Example AWA (1.3 GHz 1+1/2-cell gun)
  - High-peak field on cathode 80 MV/m
  - Charge up to 50 nC/bunch (with up to 16 bunches I consecutive L-band buckets
  - Next gen gun: symmetrized up to quadrupolar component
  - Mostly for R&D – not facility-like experience/reliability

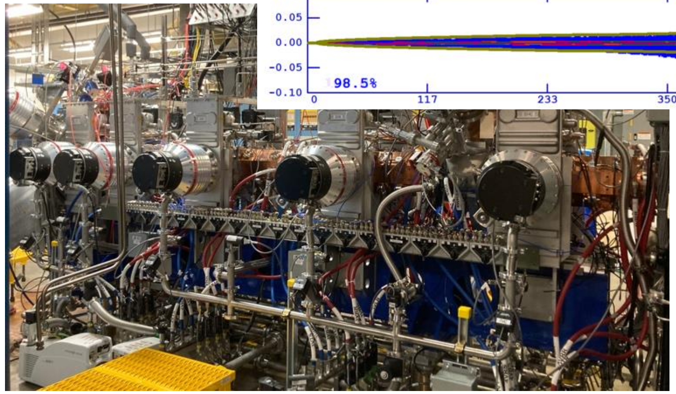


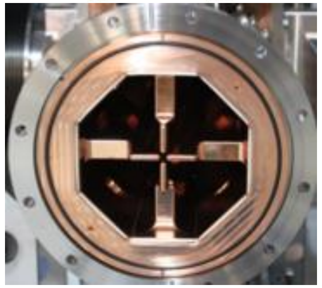
PhysRevAccelBeams.28.043401

BEAM FORMATION (III): PROTONS

Improving formation of intense proton beams







Communication from H. Ren (ORNL)

- **Radio-Frequency Quadrupole (RFQ) Performance and Lifetime Concerns**: Based on the performance of past versions of RFQs at SNS, the long-term operational lifetime of RFQs with consistent high performance is challenging.

- **Ongoing RFQ Development at SNS**: A new RFQ development effort is underway at SNS to explore innovative design concepts aimed at:
  - Accommodating higher beam loading,
  - Minimizing beam loss within the cavity,
  - Reducing performance degradation over time,
  - Enhancing overall beam brightness.

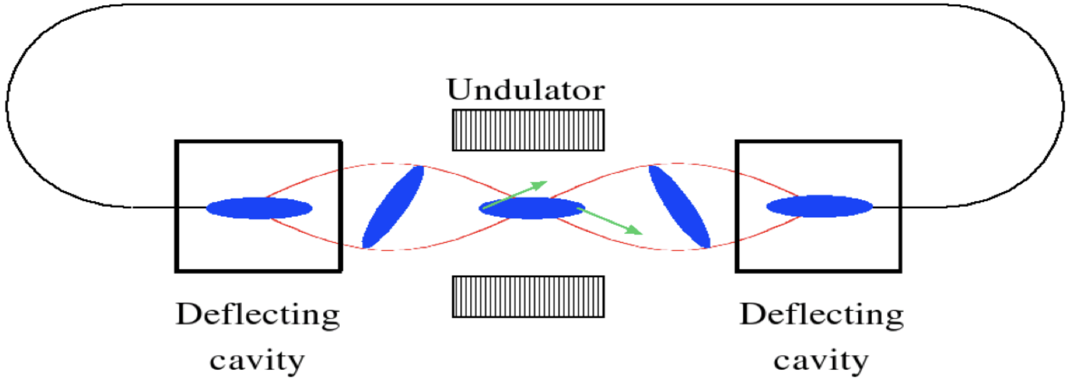
- Low-frequency NCRF cavities are also use in early-stage transport for proton beams (higher-field generally useful)

Synergy with NP: ion-beam formation.
Synergy with HEP: intensity frontier, μCollider.
Societal applications: e.g. medical radio-isotopes

BEAM MANIPULATIONS IN STORAGE RINGS

Pushing the performances of existing or future SR-based light sources

- Reduce X-ray pulse duration could increase resolution in pump-probe experiments
- Schemes to produce shorter X-ray pulses in SR have been proposed ➡ use of deflecting cavities to impart proper (t, x') correlation on the X-ray pulse for collimation/compression
- NCRF offers a path to upgrading current SR to support short-pulse generation
- Challenges:
  - damping of LOM/HOM for high current operation in SR
  - developing design/lattice to minimize emittance degradations
  - Often require multiple frequency

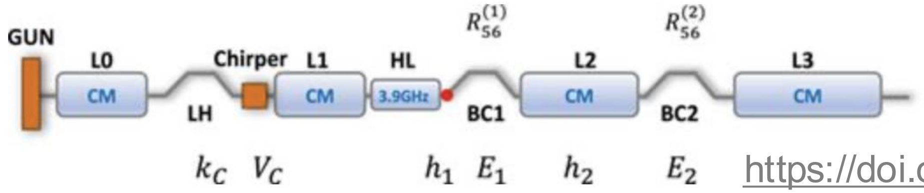


https://doi.org/10.1016/S0168-9002(98)01372-2

https://inspirehep.net/files/0de19e9cf0a11f52ba73852d72a3bfc0

BEAM MANIPULATIONS IN LINACS

Emerging new opportunities in Photon Sciences using tailored bunches



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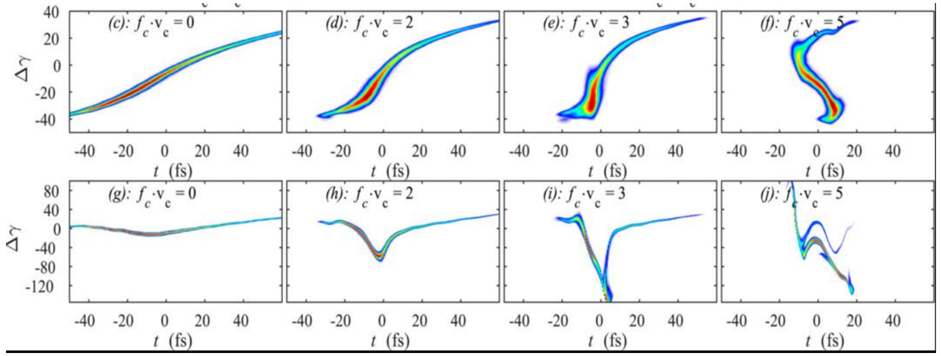
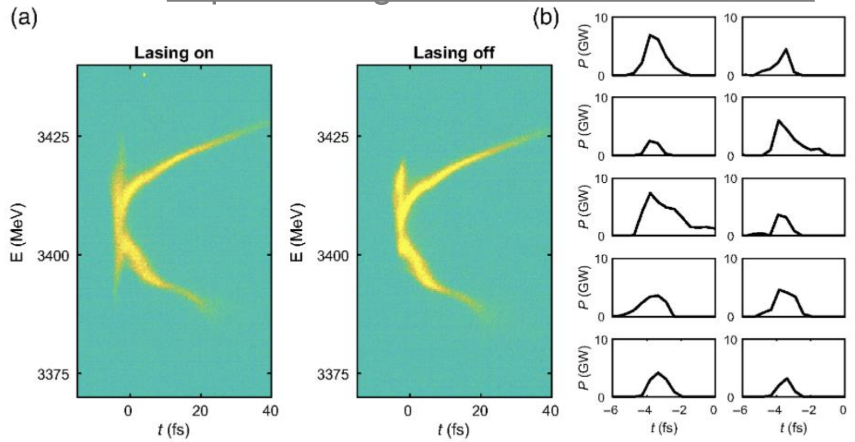


- NCRF in SCRF linac can support fast beam "on-demand"
- High-frequency structure provide precise control over local "area" in the phase space
  - Dechirper (passive, e.g. based on corrugated or dielectric-lined waveguides)
  - Comb generation (sub-THz slow-wave structures)
  - Two color FEL
- High-frequency structures also support
  - high-resolution phase space diagnostics
  - THz-pulse generation for pump-probe experiment at X-ray facilities (e.g. EuXFEL afterburner)

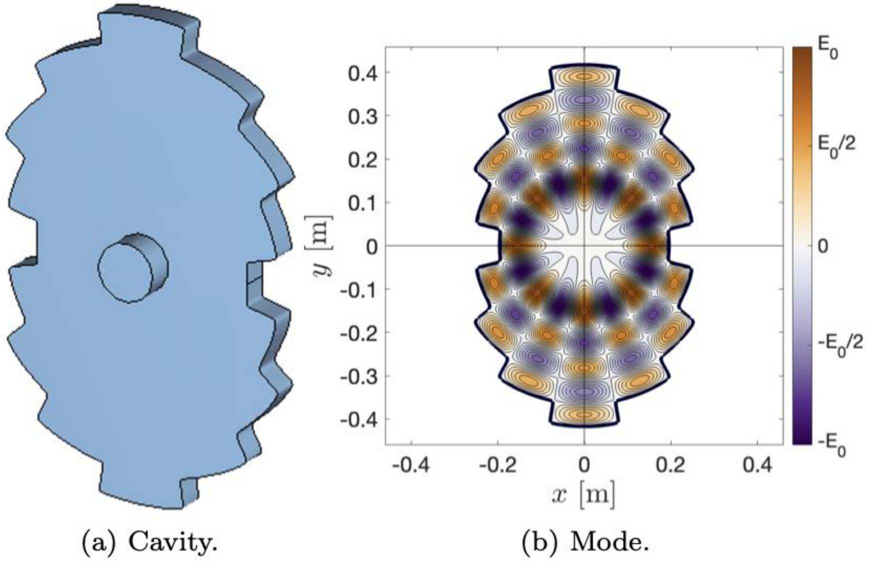
https://doi.org/10.1117/1.AP.7.2.026002



SUMMARY

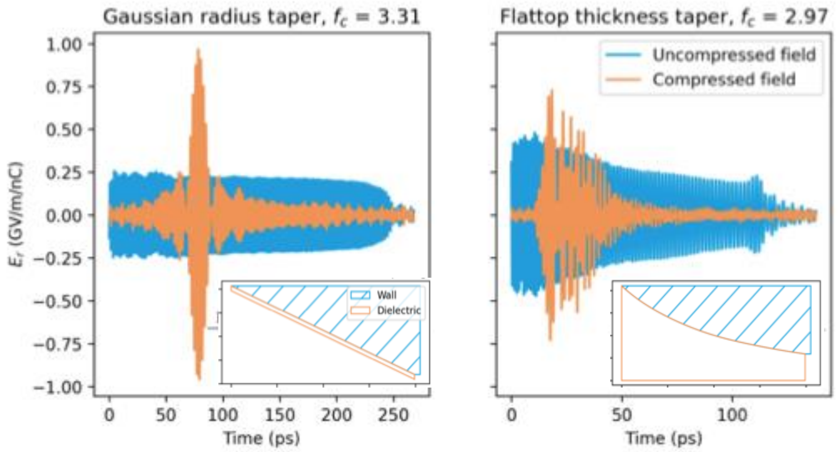
Final comments & Emerging Opportunities

- **Ubiquitous Role of NCRF Cavities:** NCRF cavities play a critical role in beam generation and manipulation.
- **Complementary to SRF Technology:** NCRF cavities can complement SRF technology by serving as diagnostics tools or enabling fast beam manipulation (high fields and low Q)
- **Enhanced Phase-Space Control and Beam Multiplexing:** With the ability to generate arbitrary field topologies, NCRF cavities offer potential for increased precision in phase-space control and advanced beam multiplexing.
- **High-Frequency Structures:** sub-THz structures present a promising avenue for compact ultrafast electron diffraction (UED) sources, phase-space manipulation, acceleration of low-charge high-energy bunches, and radiation generation.
- **NCRF technology critical to proton drivers** (capture, bunch formation, and early transport) for neutron generation.



(a) Cavity. (b) Mode.

https://arxiv.org/pdf/2504.12780



doi:10.1088/1742-6596/3010/1/012035