2021 snowmass Letter of Interest: Pushing Brightness and Current limits of Normal-Conducting Radiofrequency Electron Sources

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Mapping source R&D on HEP needs

HEP machines

Advanced accelerators
Linear colliders
Circular colliders

R&D directions For Electron sources Relevant to HEP

High currents -> 100s mA
Highly polarized beams
Flat beams
Pulse formats for injection in AAC

Physics and engineering requirements

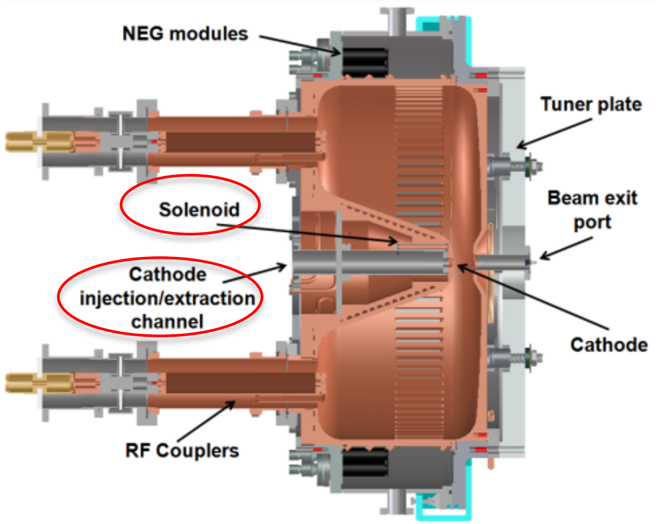
- Picometer-scale emittance
- High Charge (multi/nC)/low emittance
- Pulse trains for (PWFA)
- High precision longitudinal and transverse control:
    - Attosecond synchronization
    - Nanometer-scale stability
    - RF generation and distribution
- Magnetized beams
- Novel photocathodes
    - Increased lifetime
    - Polarized beams generation
    - Lower MTE
- Enhanced real-time modeling

Synergy with Other DOE offices

Free Electron lasers
Ultimate storage rings
Ultrafast electron scattering
...

We should leverage from work performed under BES R&D!

APEX: a Low Frequency CW-NC electron gun driving the next generation of MHz-class FELs and UED



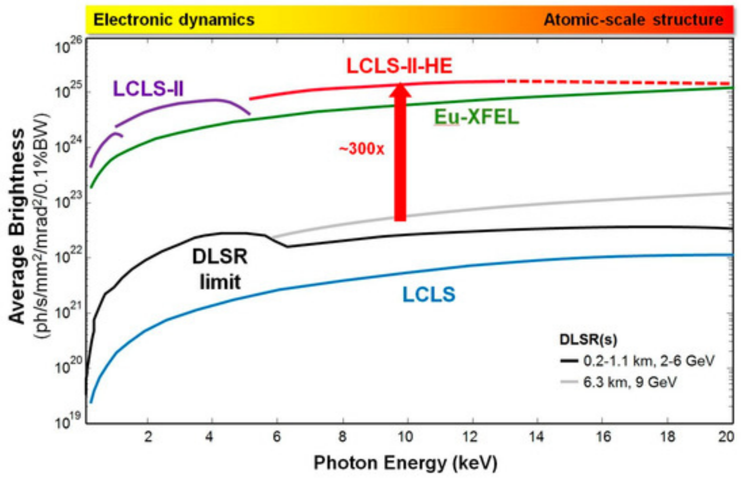
Nucl. Instr. & Meth A 599, 9 (2009)

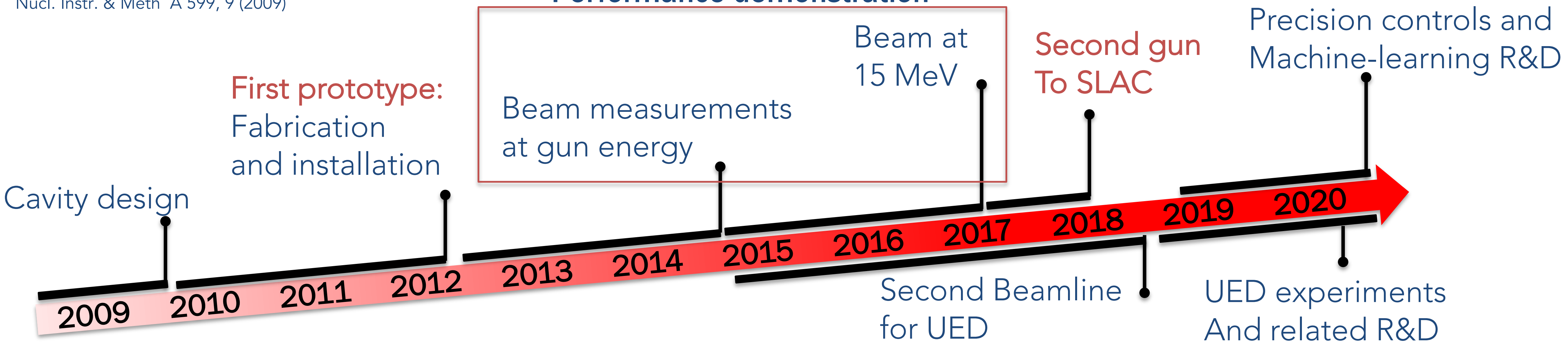
Frequency	186 MHz
Operation mode	CW
Peak wall power density	25.0 W/cm^2
Field at the cathode	> 20 MV/m
Beam energy	Up to 800 keV
base pressure	~ 10^{-11} Torr

High repetition rate

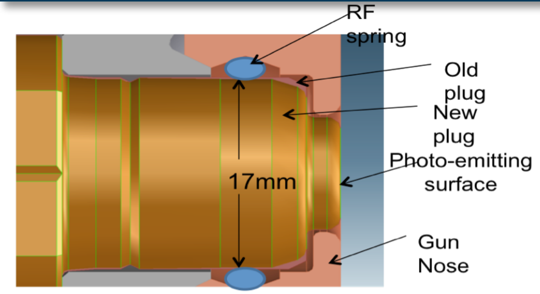
High brightness

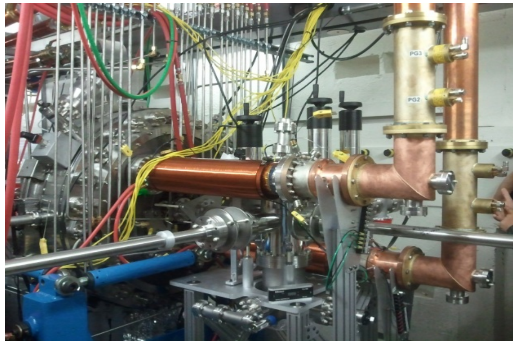
High current

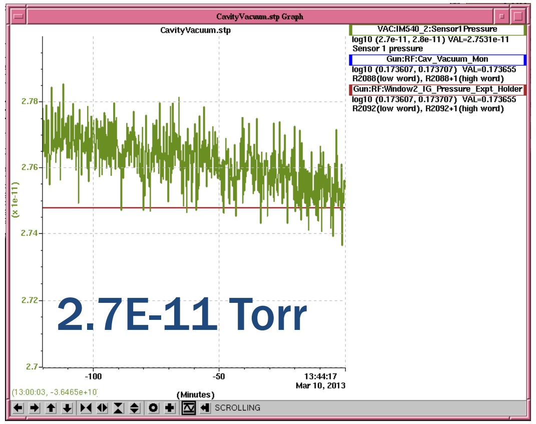




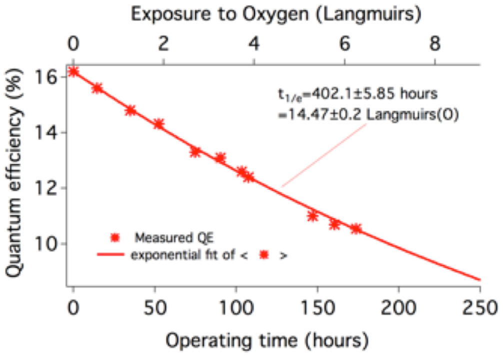
Testing new cathodes for High average current operations
(HEP relevance: electron cooling)

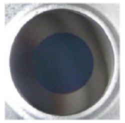


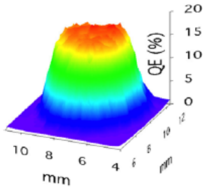


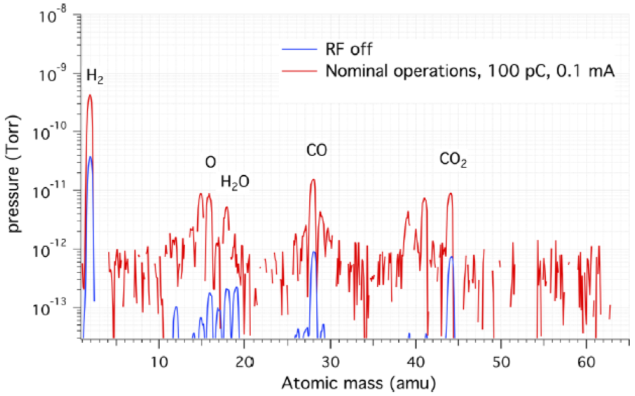


PEA Cesium Telluride Cs_2Te
-- high QE > 1%
-- for 1 MHz and 1 nC, ~ 10 W 1060nm required
-photo-emits in the UV
-robust



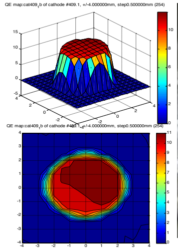


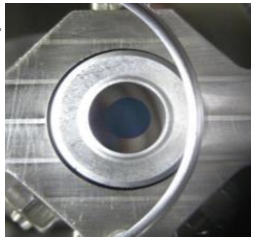


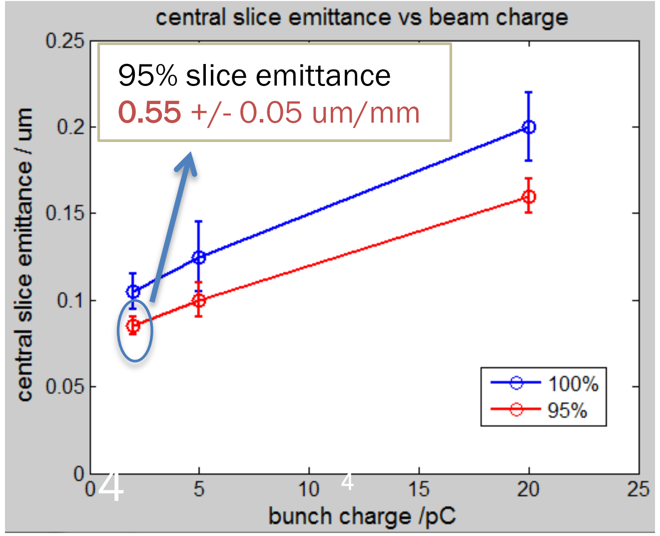


Appl. Phys. Lett. 107, 042104 (2015)

PEA CsK_2Sb, (H. Padmore's group LBNL)
- reactive; requires ~ 10^{-10} Torr pressure
-high QE > 1%
- photoemits with green
- for nC, 1 MHz, ~ 1 W of IR required

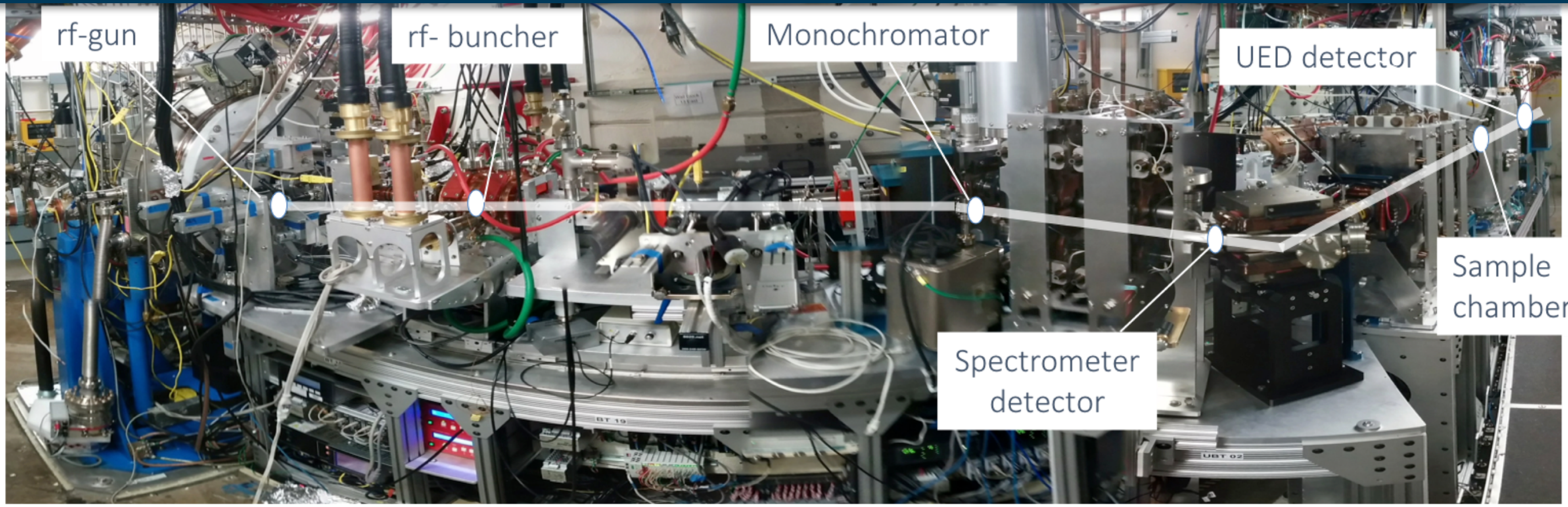






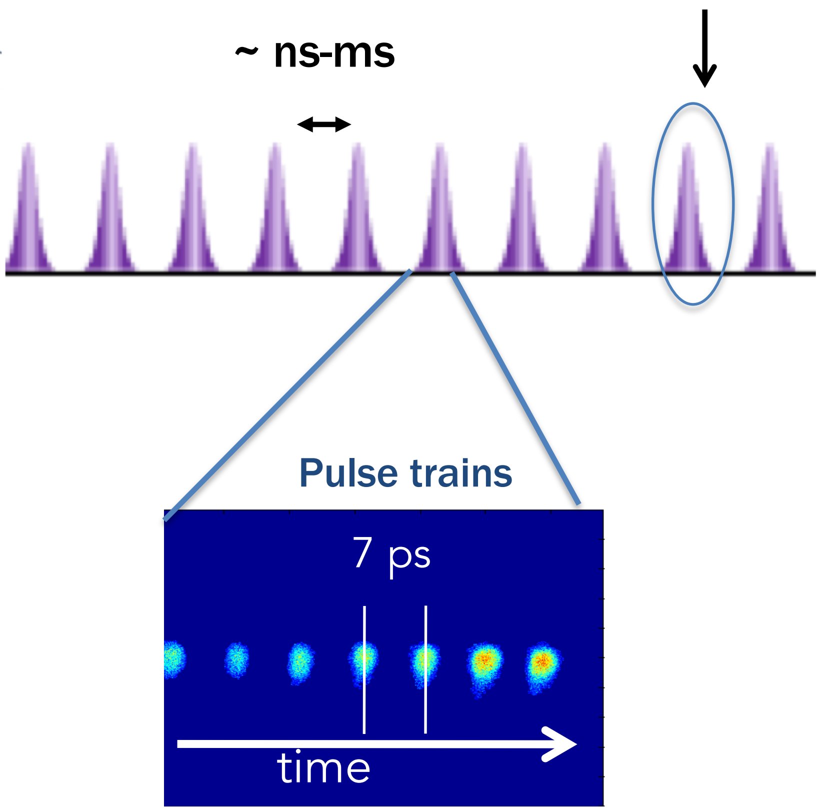
HiRES: A compact beamline for 6D beam characterization

(HEP relevance: beam shaping, flat beam production and characterization, test pulse formats for AAC)

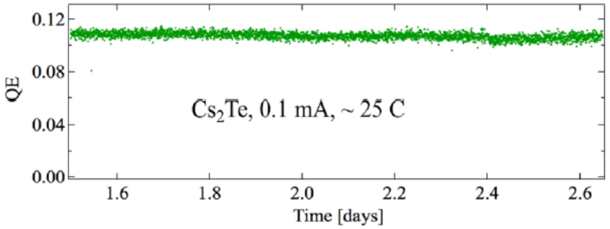


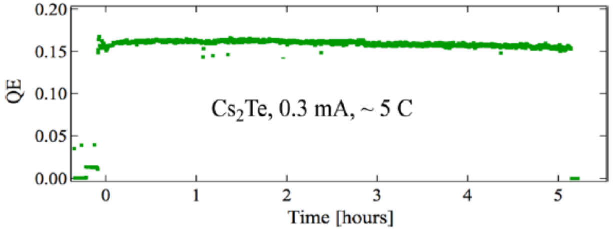
JPB: Atom. and Mol. And Opt. Phys. Vol 49, 2016

~ 10^5-10^9 e-
~10 fs-1000 ps

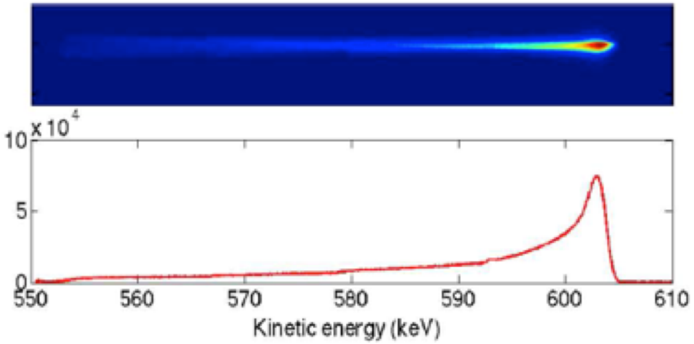


mA-class average currents



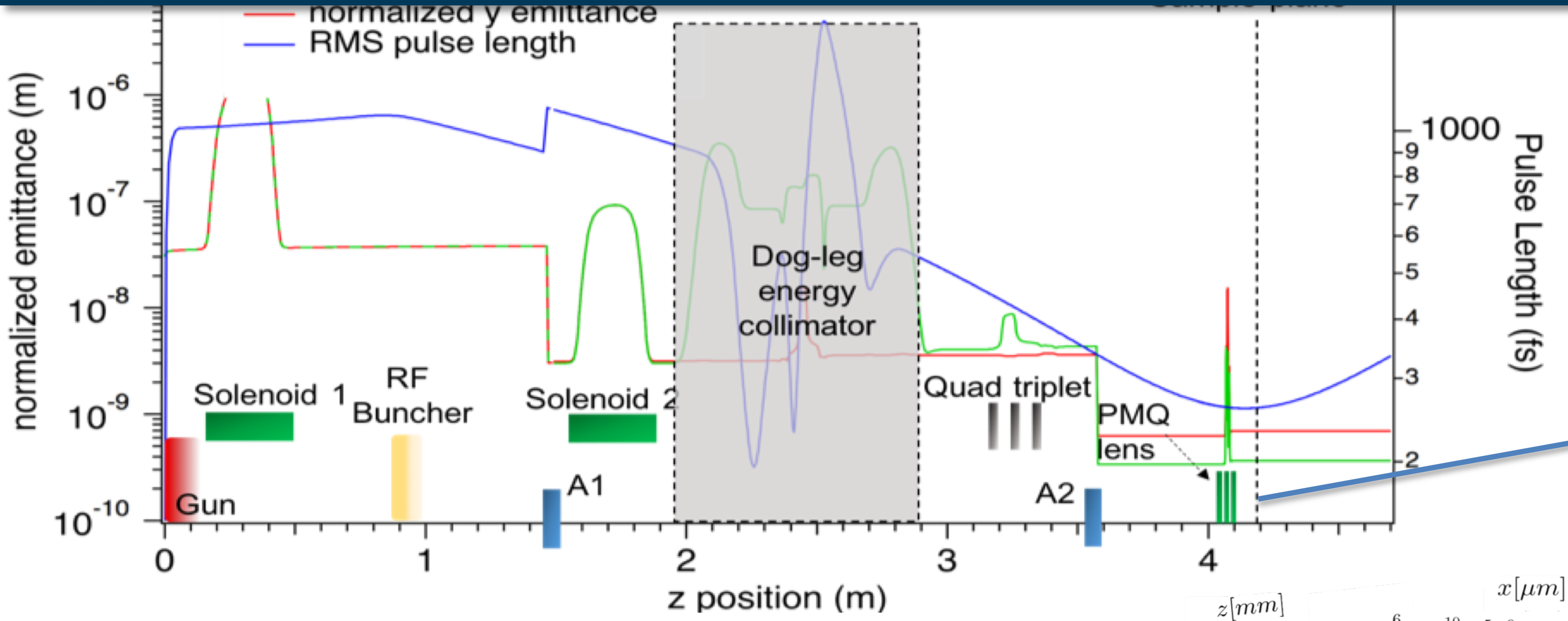


High dynamic range diagnostic

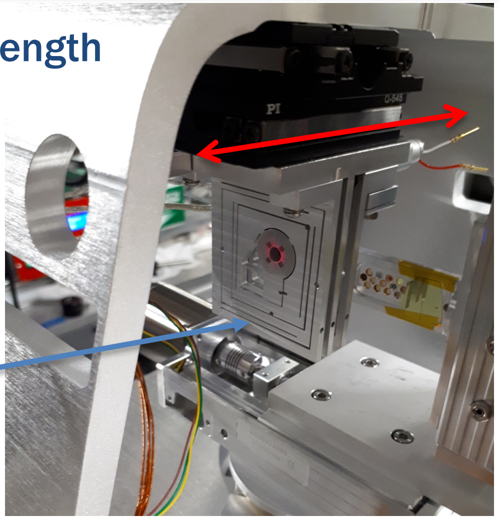


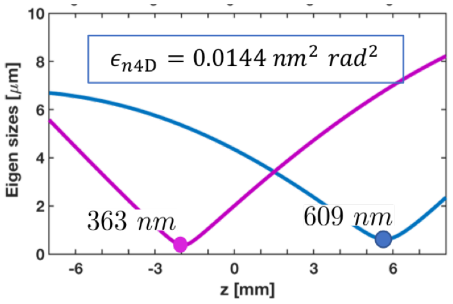
Phys. Rev. ST Accel. Beams 15, 103501 (2012)
Phys. Rev. ST Accel. Beams 18, 013401 (2015)

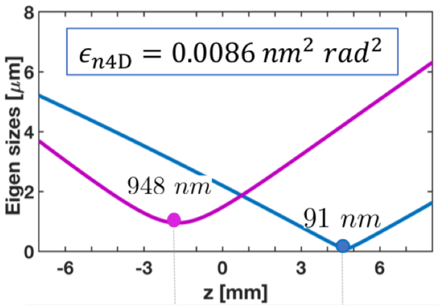
Generation of relativistic nanobeams
(HEP -> injection in AAC, testbed for nanoscale beam control and diagnostic in colliders)

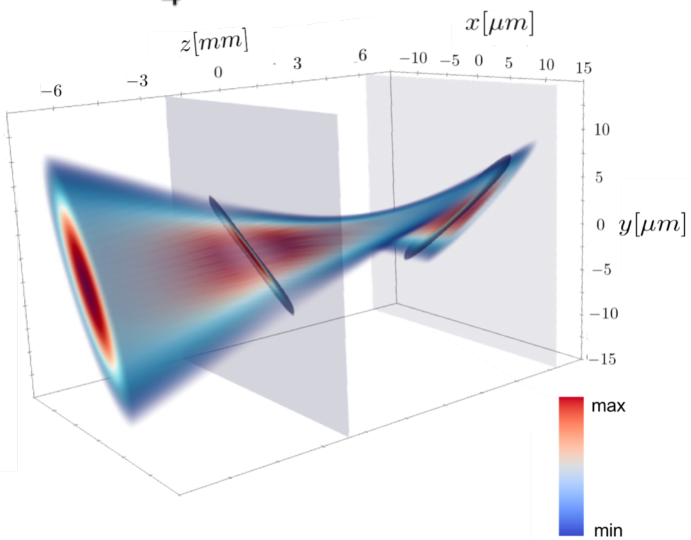


Short-focal length quad setup

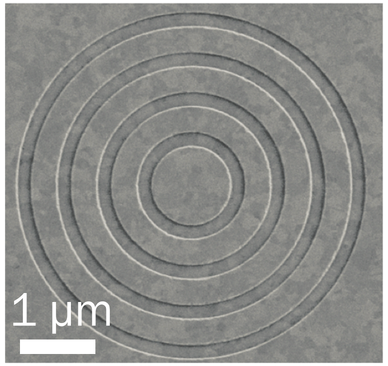








Nano-photoemitter

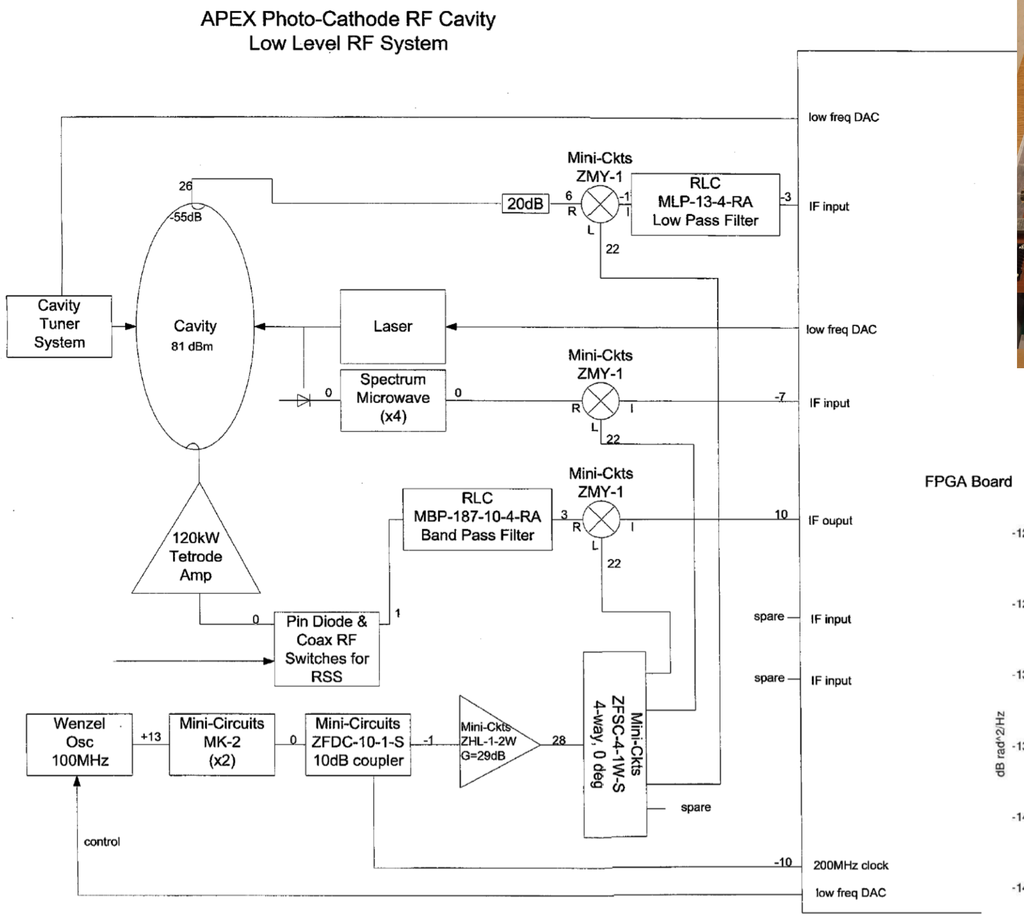


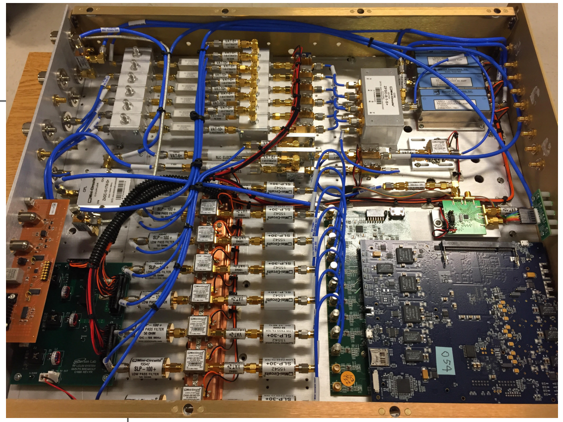
Nat. Comm. Physics, 2(1), 2019

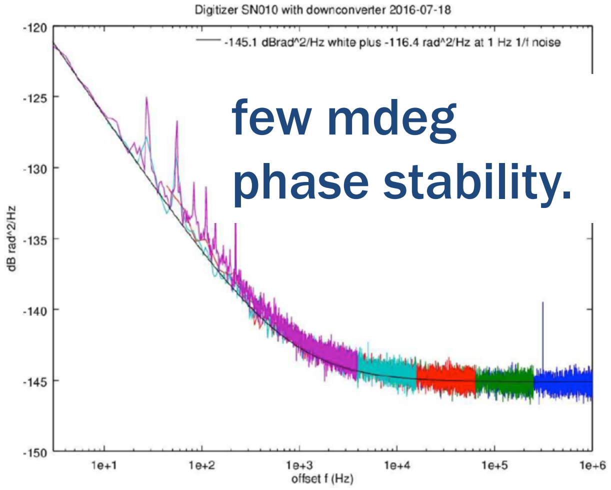
Durham, Phys. Rev. Applied **12**, 054057, 2019

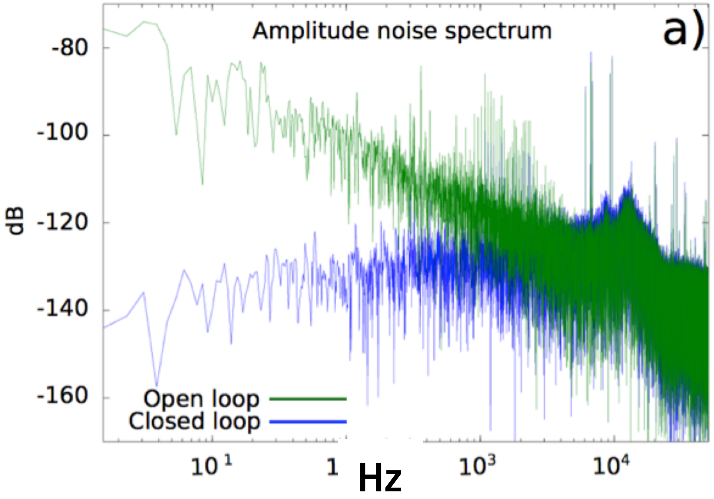
High precision controls

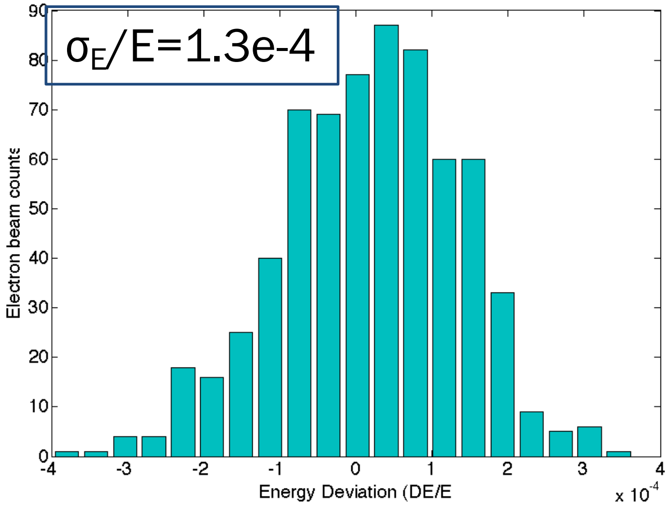
(HEP-> crosscutting theme, control of temporal and transverse stability of the beam in accelerators)











How does the future look like: ML-based real-time adaptive feedbacks

(HEP-> crosscutting theme, control of temporal and transverse stability of the beam in accelerators)

What are the advantages of a ML native CS?

- From local to global real-time feedbacks
  - Performance improvement
  - Failure predictions

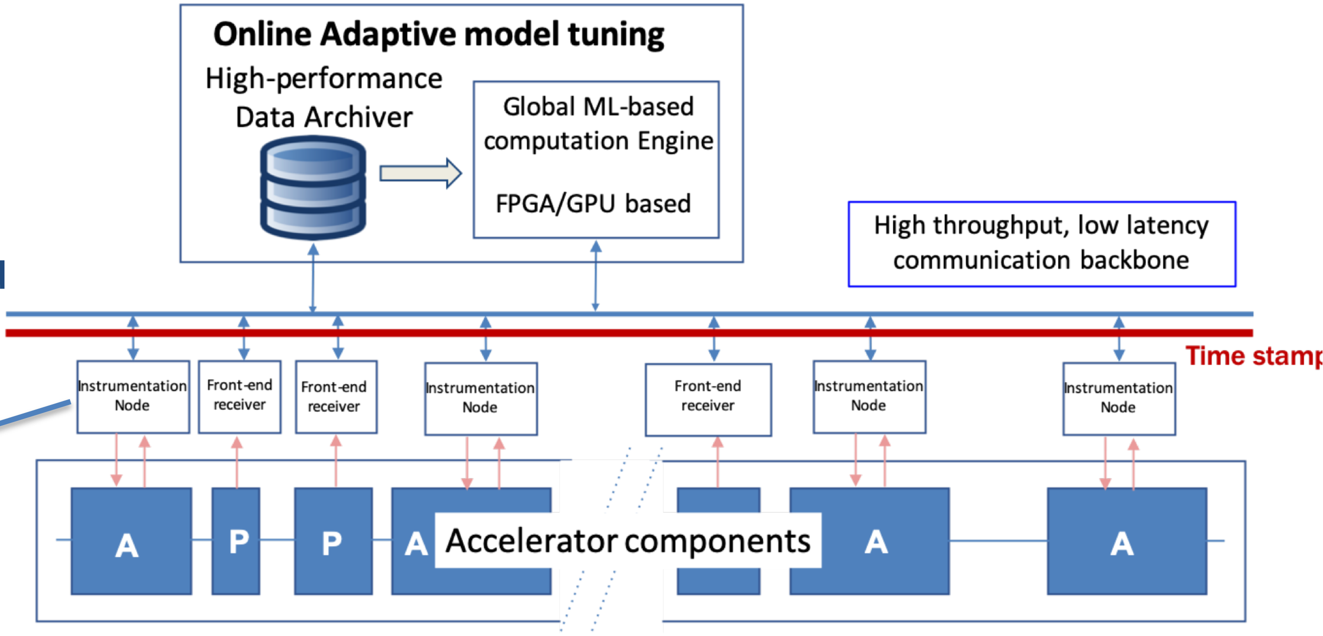
How do we effectively use ML for accelerator control?

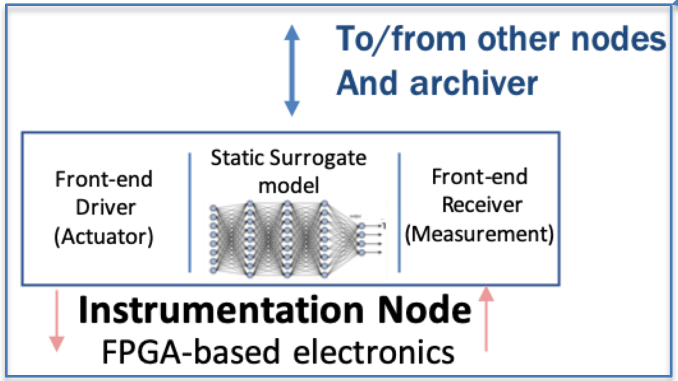
- Include surrogate models into the control electronics
- Use supervised learning to continuously improve the model and catch time-varying effects.

How do we choose the hardware?

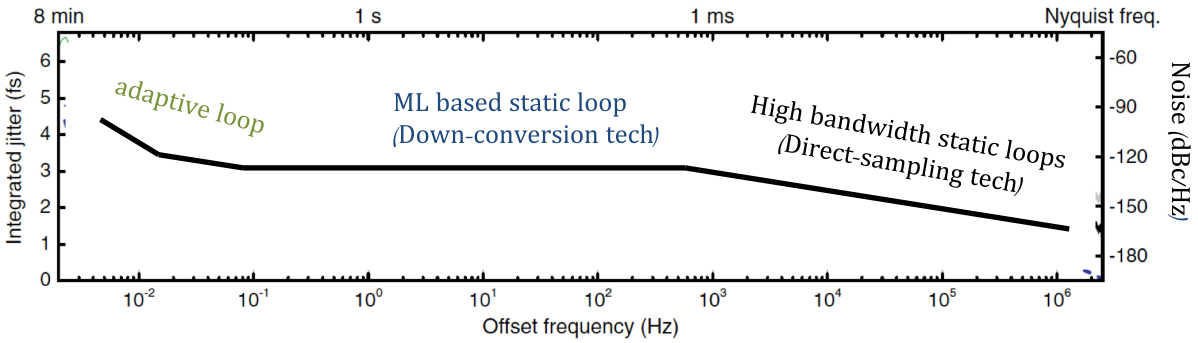
- Optimize for noise reduction in specific frequency bands

Design of an *Holistic* control system





- Fast local loops (ns)
- ML-based global optimization
- ML models changing with time



Large unexplored parameter space in performance and applications

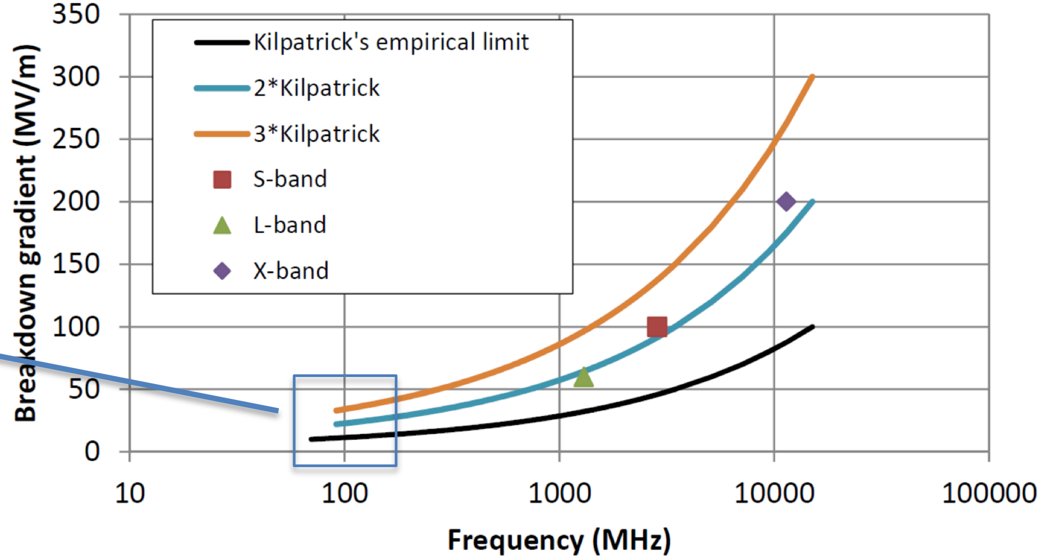
(HEP->higher brightness would lead to smaller emittance and increase the final luminosity of the machine)

NCRF CW technology has not been fully optimized

- APEX gun was designed with a conservative nominal accelerating field values.
- Experience from continued operations (since 2012) suggests large room for improvements (no RF breakdown events).
- Electron gun accelerating field is limited by available RF power at site, not by power density or RF breakdown
- The second-generation of NCRF CW guns has not been fabricated yet, differently from other gun technologies (DC, SRF, GHz-NCRF)
- Efforts in Europe and China to design and/or fabricate improved versions of the VHF gun
- LBNL is working on a new design with improved accelerating field and output energy

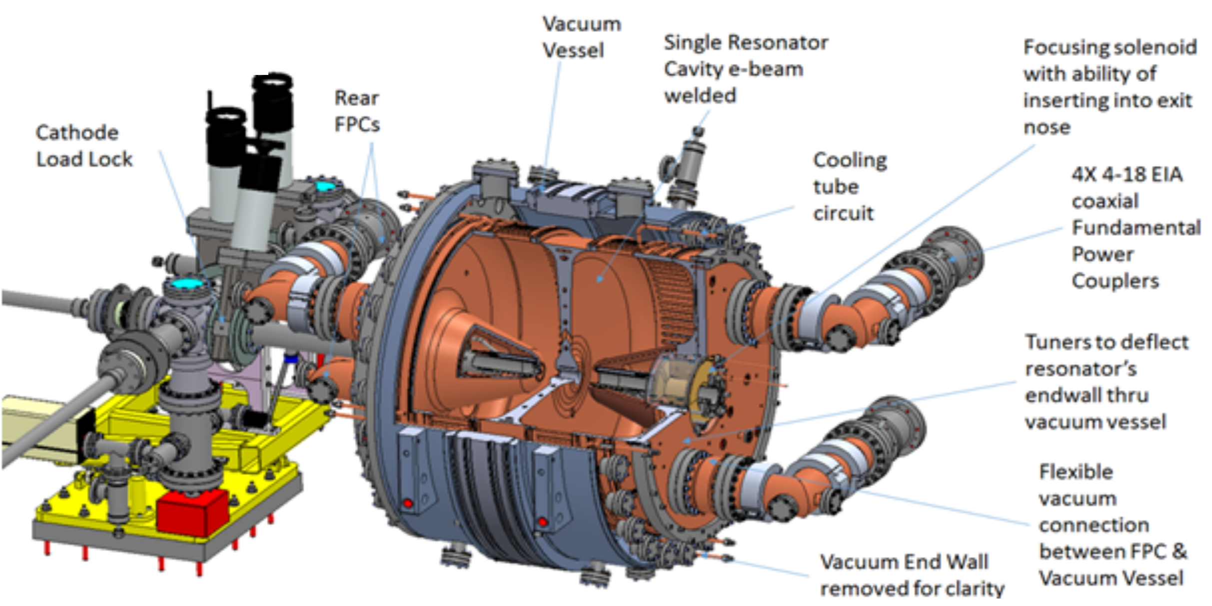
@ 200MHz

$2E_k$=30MV/m

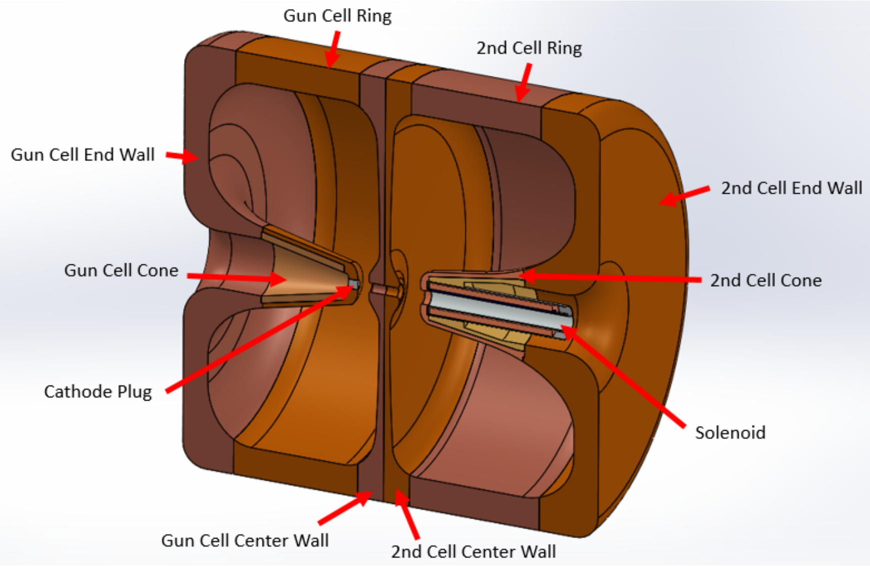


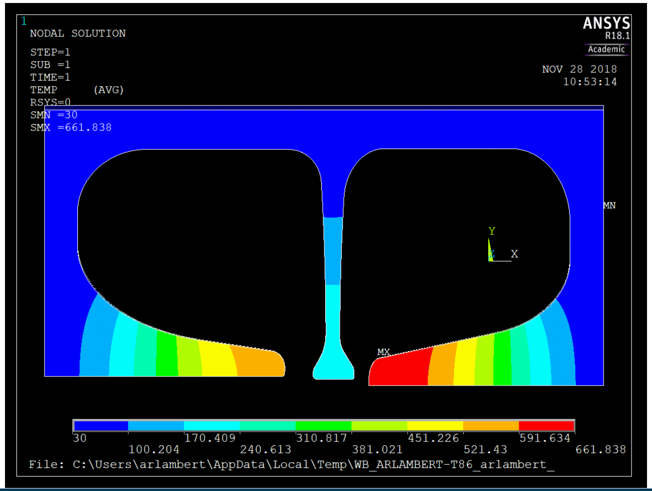
Next-generation APEX

(HEP->higher brightness would lead to smaller emittance and increase the final luminosity of the machine)



	APEX gun	APEX-2 gun Cell 1	APEX-2 gun Cell 2	
Frequency	185.7	162.5	162.5	MHz
Peak acceleration field	19.5	34	25	MV/m
Gun voltage	750	820	820	kV
Average RF power	90	91	85	kW
Shunt impedance	6.3	7.3	7.8	Mohm
Peak surface field	24.1	37	25	MV/m
Peak thermal power density	25	32	30	W/cm^2
Diameter/Length	69.4/35.0	78.6/38.7	78.2/36	cm

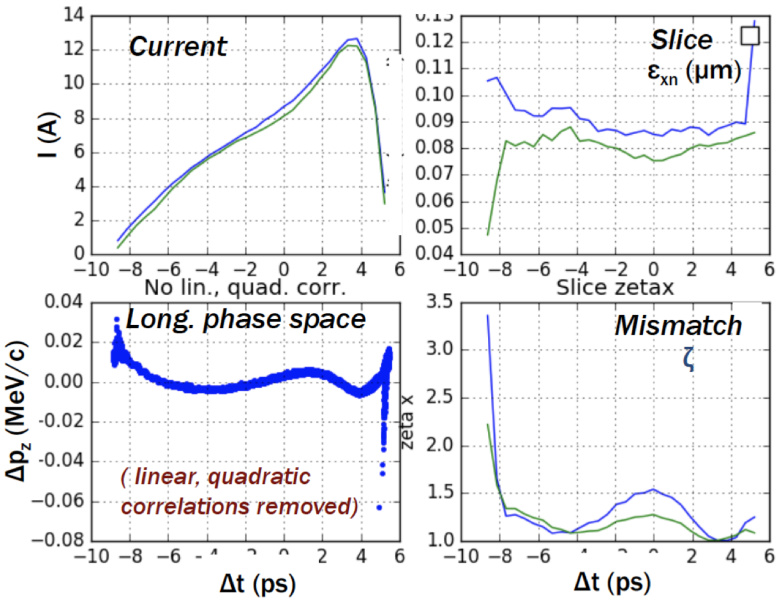




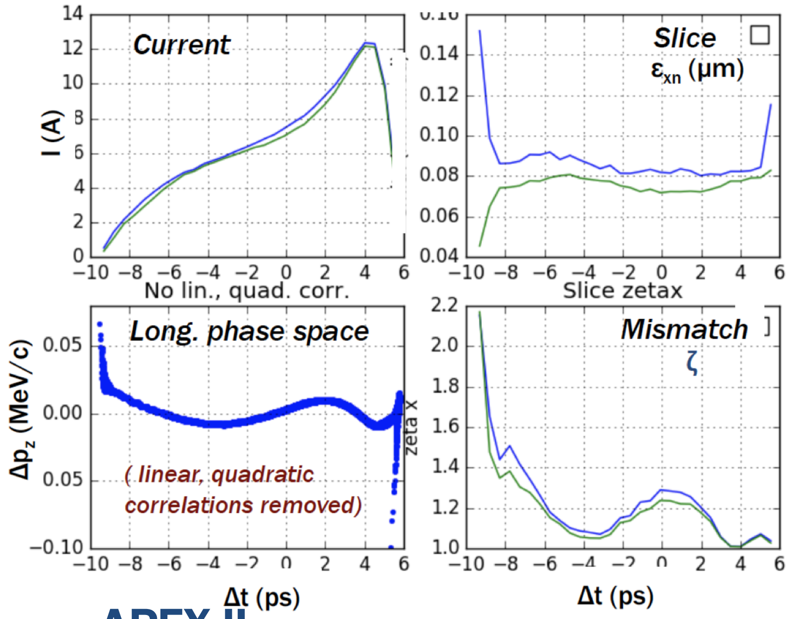
Emittance and peak current performance at 100 MeV

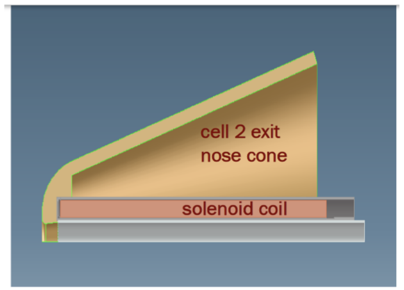
(HEP->higher brightness would lead to smaller emittance and increase the final luminosity of the machine)

30 MV/m Solution (250K particles)



35 MV/m Solution (250K particles)





Solenoid quality factor improved by 2.7

Current APEX gun

Parameter	LCLSII
ε_{xn} (100%) [μm]	0.1881
ε_{xn} (95%) [μm]	0.1621
Peak current [A]	12.0
KE [MeV]	88.0
HOM* [keV/c]	3.25

APEX-II

Parameter	30 MV/m	35 MV/m
ε_{xn} (100%) [μm]	0.1033	0.0968
ε_{xn} (95%) [μm]	0.0897	0.0839
Peak current [A]	12.0	12.0
KE [MeV]	115	124
HOM* [keV/c]	3.66	6.63

Main contributions to improved performance:

- Higher cathode field allow smaller laser spots
- Higher output energy allow for smaller e-beams
- Embedded solenoid in second cavity minimize aberrations

Conclusions

- NC-RF CW cavities provide a perfect setup to test the generation of electron beams for HEP-relevant applications
- The MHz repetition rate has been successfully used to produce mA-class current, and/or to lower the beam emittance to picometer-scale
- Vacuum levels reached during operations allowed operations with semiconductor cathode materials.
- The cavity is fully compatible with strong magnetic fields at the cathode (for tests with flat beams)
- HEP requirements for electron sources are synergetic but more challenging than BES. Beam parameters need to be pushed beyond what has been demonstrated (no clear showstopper at the moment)

- It is a mature technology, with a large room for improvement.
- The RF design of the NC-CW RF cavity has been optimized around 1 accelerating field value, which has been demonstrated to be a conservative working point.
- There hasn't been serious R&D to understand the limitation of such technology and how it compares with others.
- A full RF design of the next generation of the APEX gun has been carried out at LBNL. The design includes the downstream low energy beamline for optimal performance.