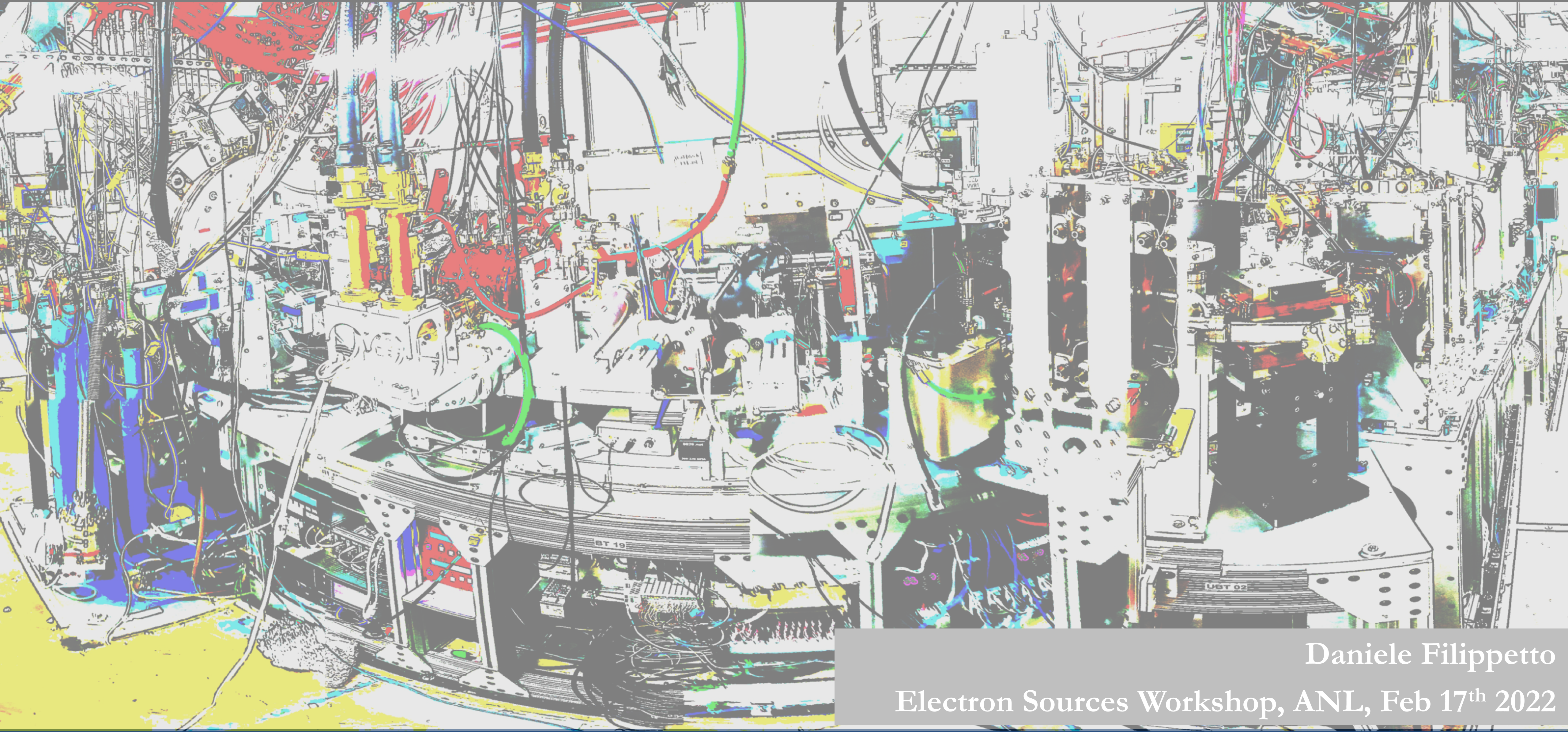
CW Normal-Conducting RF sources for future linear colliders



Daniele Filippetto

Electron Sources Workshop, ANL, Feb 17th 2022

Some Background

In linear colliders the Luminosity is achieved by small beam sizes at IP -> strong beam-beam effects!

$$L = f_{\text{coll}} \frac{N_b^2}{4\pi\sigma_x^*\sigma_y^*} F$$

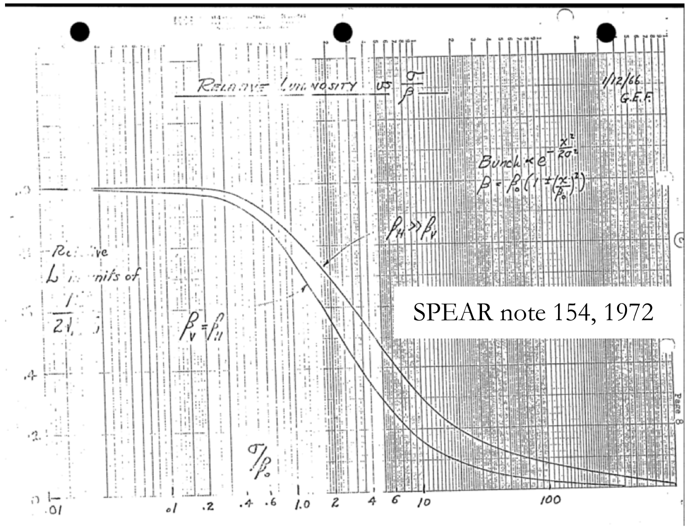
geometric factor (crossing angle, hour glass, pinch, …)

Parameter	Symbol [unit]	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	500	380	3000
Particles per bunch	N [10^9]	20	5.2	3.72
Bunch length	σ_z [μm]	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	474/5.9	143/2.9	40/1
Emittance	$\varepsilon_{x,y}$ [μm/nm]	10/35	0.95/30	0.66/20
Betafunction	$\beta_{x,y}$ [mm/mm]	11/0.48	8.2/0.1	6/0.07
Bunches per pulse	n_b	1312	352	312
Distance between bunches	Δz [mm]	554	0.5	0.5
Repetition rate	f_r [Hz]	5	50	50

FCC e-e+

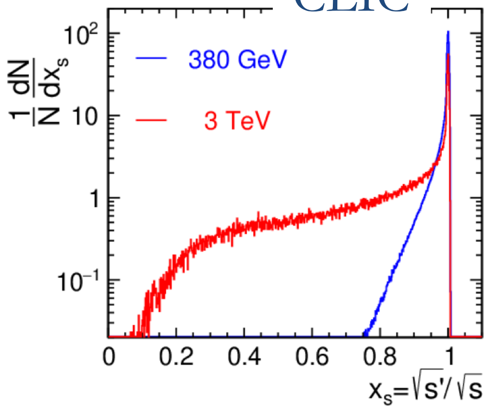
rms bunch length with SR / BS [mm]	**4.32 / 15.2**	**3.55 / 7.02**	**2.5 / 4.45**	**1.67 / 2.54**
horizontal rms IP spot size [μm]	**10**	**21**	**14**	**39**
vertical rms IP spot size [nm]	**34**	**66**	**36**	**69**

”hour glass” effect



“beamstrahlung”

CLIC



R&D requirements for Electron sources

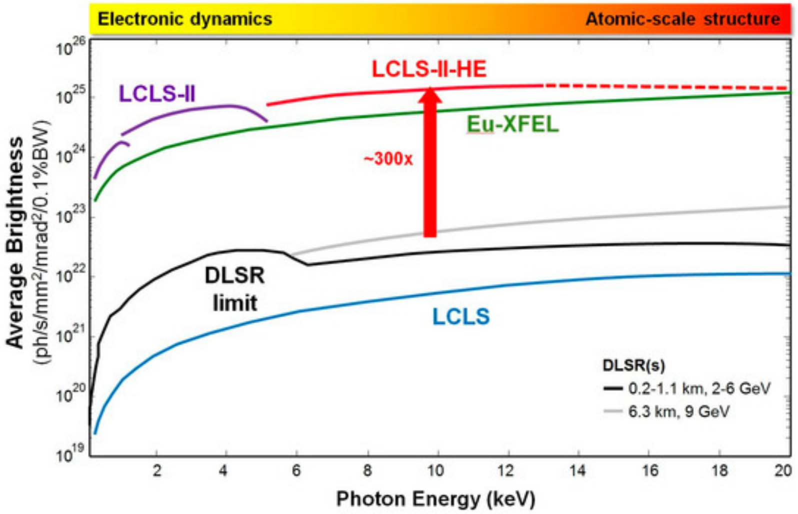
- <u>**Electron beam R&D for HEP/NP colliders**</u>
  - **Brightness, Brightness, Brightness…**
    - Multi-nC beams with um-scale emittance
    - Nanoscale beams with picometer emittance
    - Short pulses (Longitudinal emittance)
  - **Average current/pulse formats**
    - Tens-of-kHz rep rates for AACs
    - Bust-mode operations
  - **Polarization**
  - **Flat beams**
    - Large emittance ratios btw x and y planes
  - **Stable and reliable**

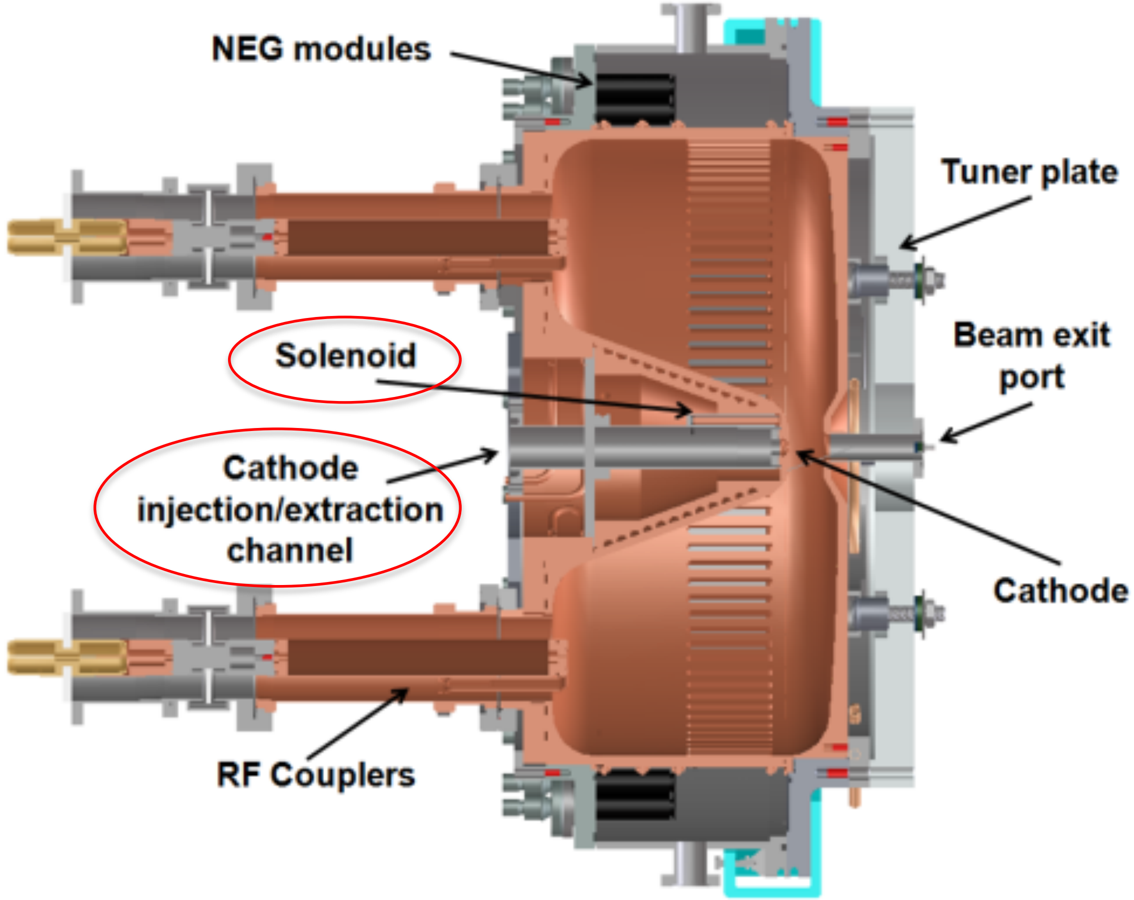
- <u>**Electron source requirements:**</u>
  - **High Accelerating fields**
  - **High duty-factor (depending on particular concept)**
  - **Provide environments for delicate cathodes**
    - High QE, Spin-polarized
  - **Back-illumination (optional for generation of nanoscale beams)**
  - **Compatibility with strong magnetic fields at the cathode**
  - **Low dark current transport**
  - **High precision control RF fields and lasers**
    - Beam loading compensation
    - High precision RF measurements
    - Low latency feedback systems
    - Bandwidth requirements depend on pulse format
  - **High precision diagnostic for nanoscale beams**

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)
Phys. Rev. ST Accel. Beams 15, 103501 (2012)
Phys. Rev. ST Accel. Beams 18, 013401 (2015)
Appl. Phys. Lett. 107, 042104 (2015)

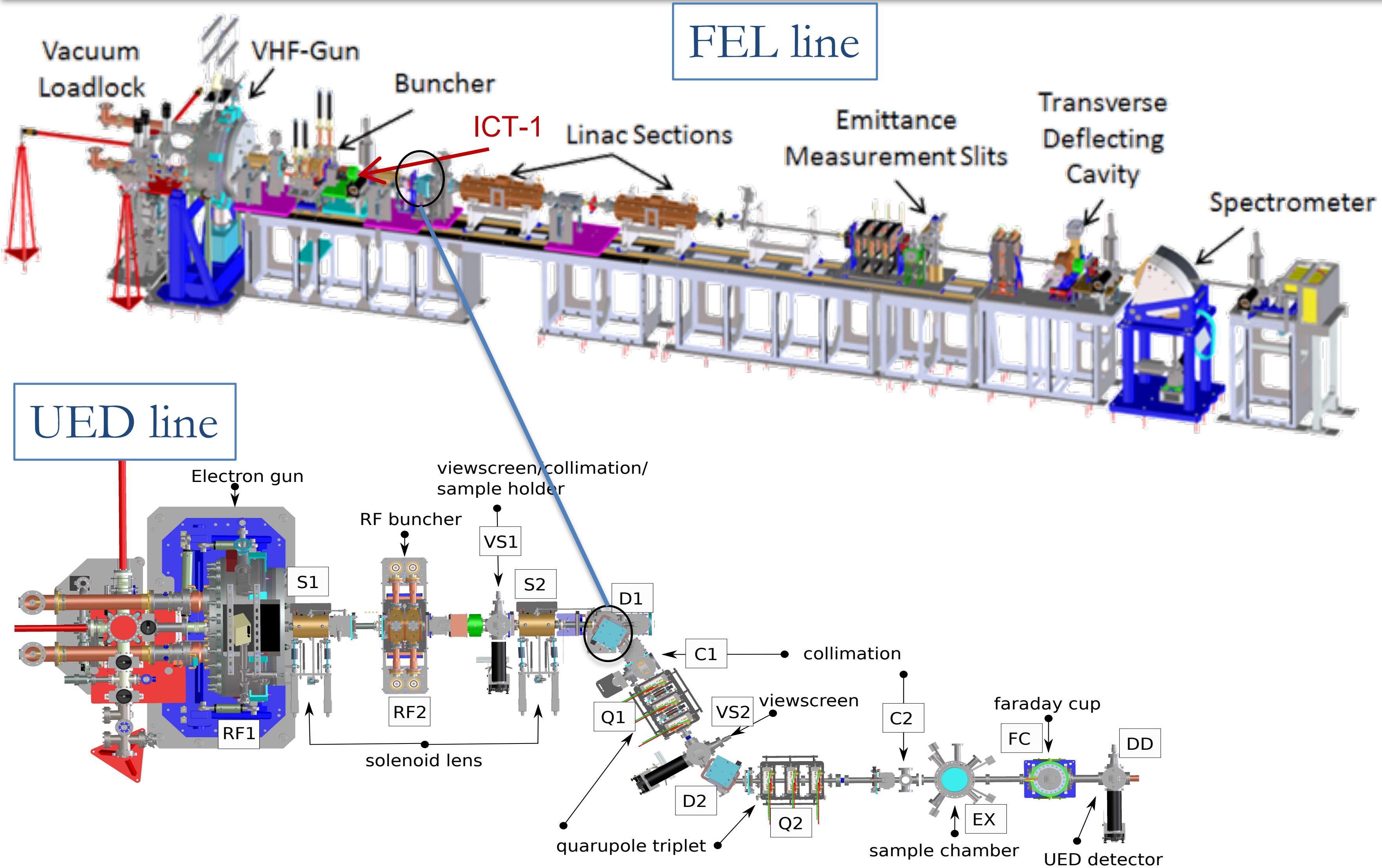
Frequency	186 MHz	repetition rate
Operation mode	CW/pulsed	
RF power	90 KW	
Peak wall power density	25.0 W/cm^2	
Field at the cathode	> 20 MV/m	brightness
Beam energy	Up to 800 keV	
base pressure	~3 10^{-11} Torr	average current





R&D efforts on electron gun technology is synergistic between many different DOE offices

The HiRES accelerator



15 MeV
1E-4 Duty Cycle

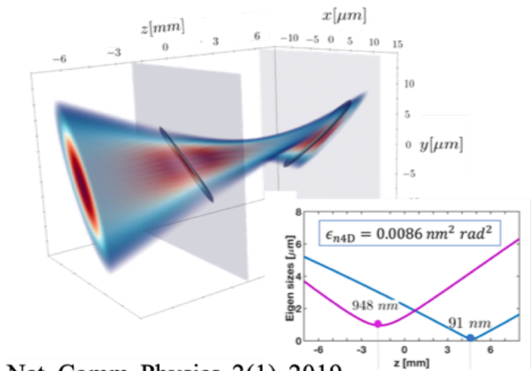
<~ 1MeV
100% Duty Cycle
Max repetition rate 185.7 MHz
Minimum bunch separation 5 ns

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

A platform for electron-based applied science at technology

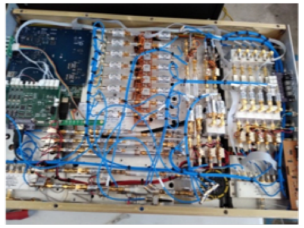
Transverse and longitudinal control

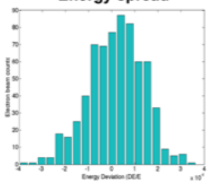
Nanometer-scale high brightness beams



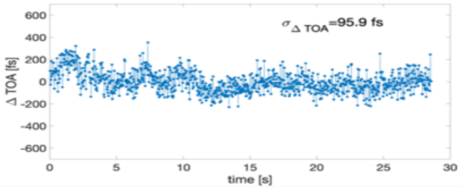
Nat. Comm. Physics, 2(1), 2019.
PRAB, 22 082801, (2019).

Longitudinal phase space parameters



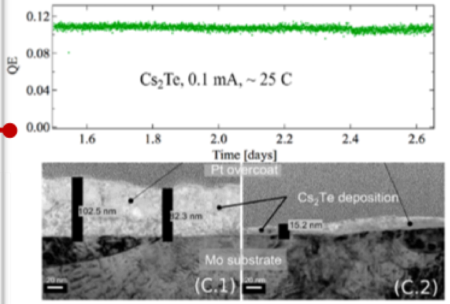


σ_E/E = 1.3x10^{-4}

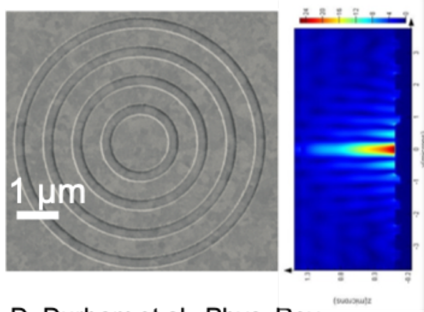


D. Filippetto & H. Qian. J. Phys. B.-At. Mol. Opt. 2016.

High brightness sources

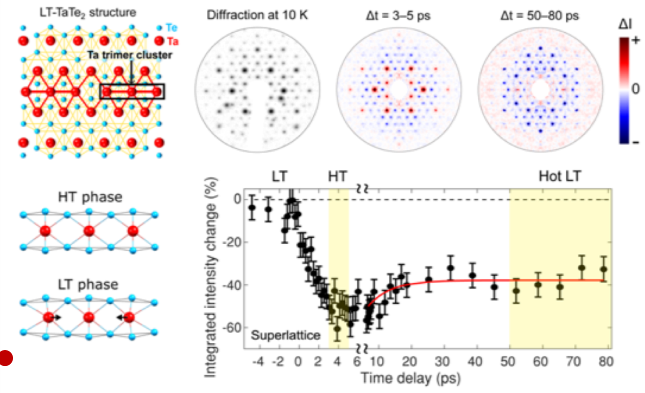


D. Filippetto et al.,
Appl. Phys. Lett. 107, 042104 (2015);



D. Durham et al., Phys. Rev. Applied **12**, 054057, 2019

Applications of bright beams

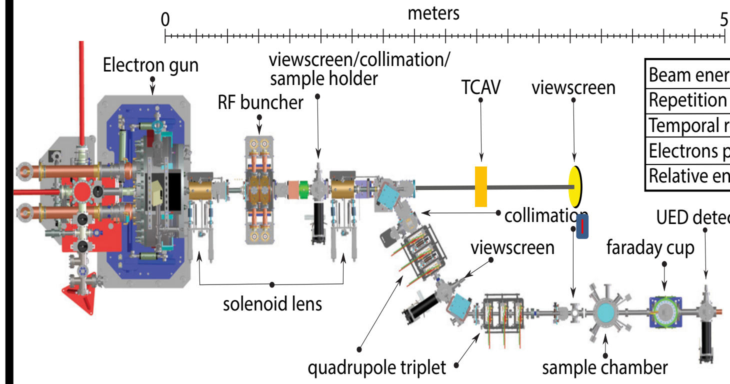


K. M. Siddiqui, et al., Commun Phys 4, 152 (2021).

GARD-ABP grand challenges

beam intensity

beam quality

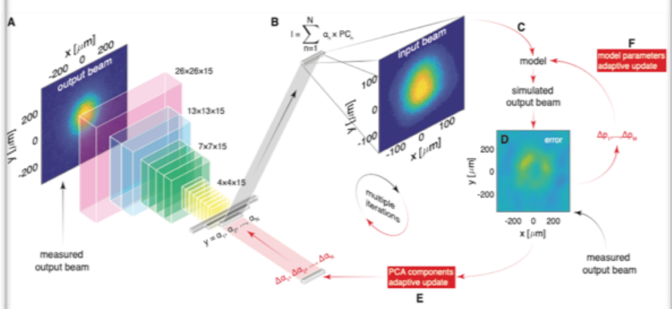


Beam energy	700-900 keV
Repetition rate	1-10^6 Hz
Temporal resolution	250 fs - 1000 ps
Electrons per pulse	1-10^8
Relative energy spread	10^{-3} - 10^{-4}

beam control

beam prediction

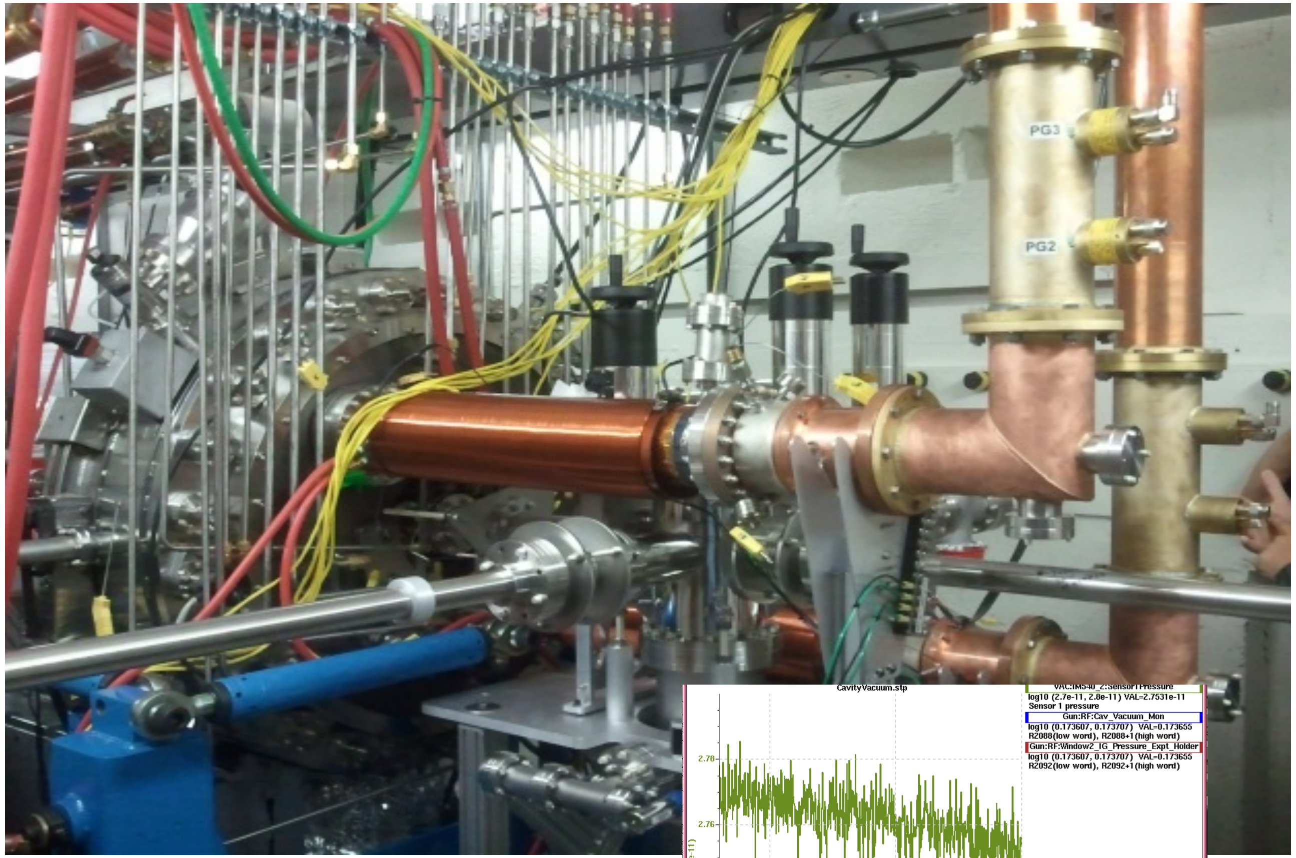
Adaptive ML techniques for accelerators

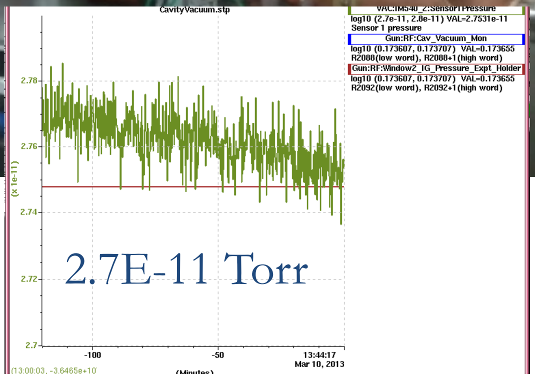


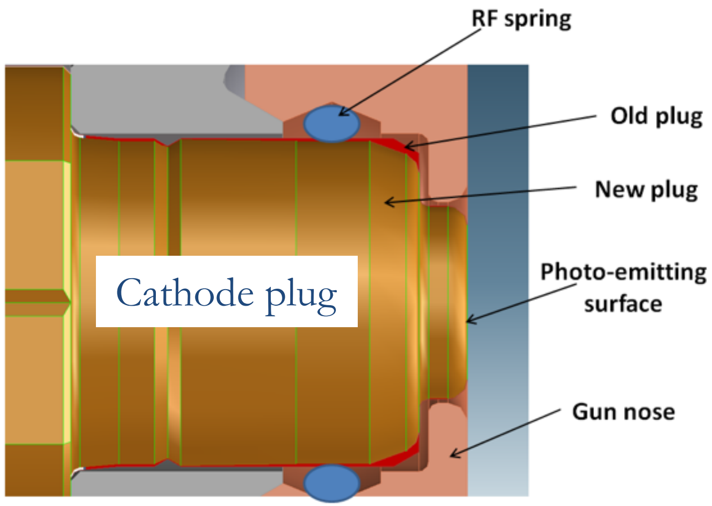
A. Scheinker, F. Cropp, S. Paiagua, and D. Filippetto, Sci Rep **11**, 19187 (2021).

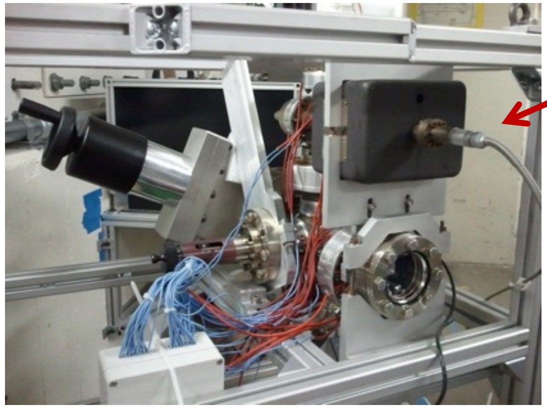
Experimental setup for testing novel photocathodes

Adapted version of the INFN/PITZ/FLASH load-lock system







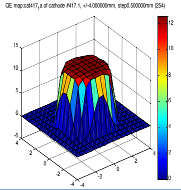


Vacuum "suitcase" compatible with long-distance transportation (NEG pump)

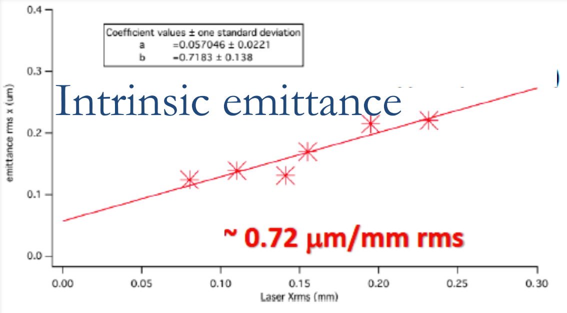
Successfully transported Cathodes from INFN-LASA to LBNL

High quantum efficiency photocathode tests: Cs_2Te

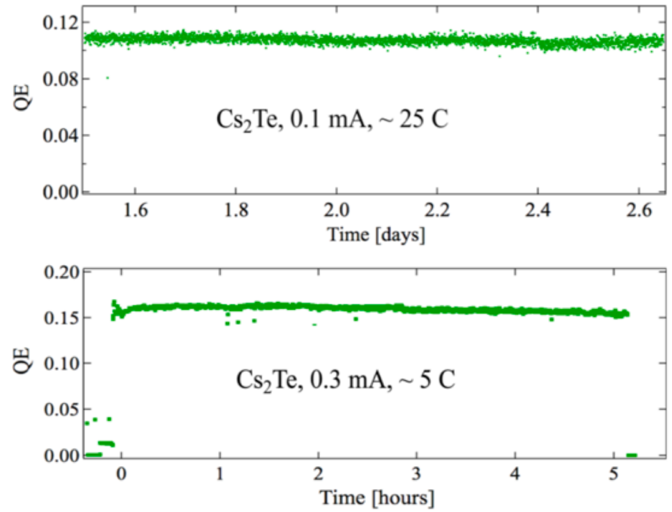
20 nm of Te + 80n nm of Cs, from LASA_INFN



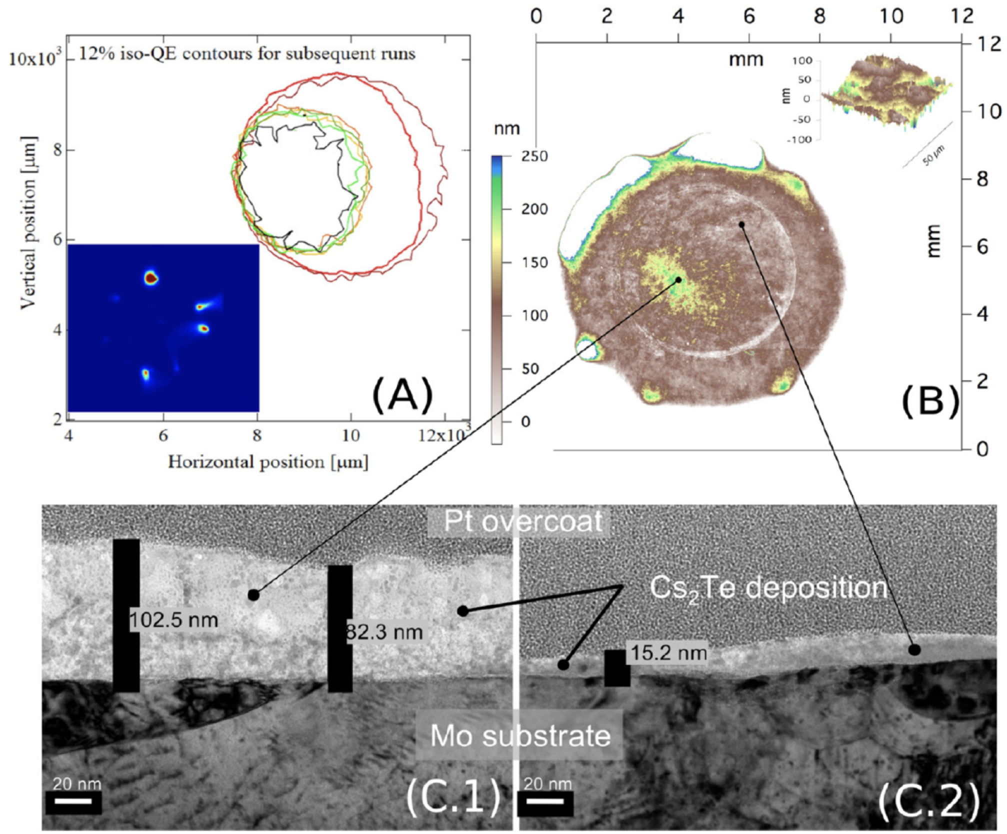
Intrinsic emittance



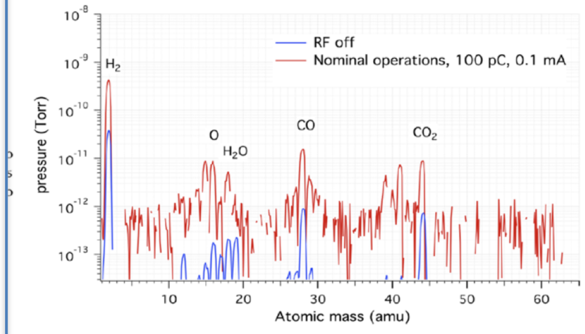
High current measurements:

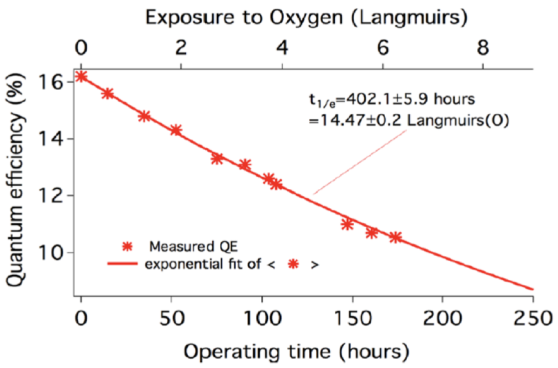


Evidence dark-current driven cathode sputtering



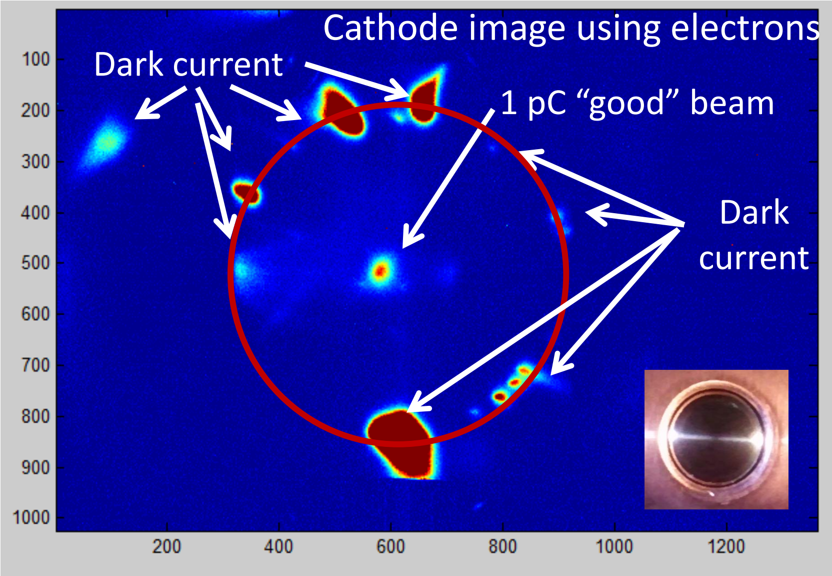
Operations inside high RF field environment: lifetime

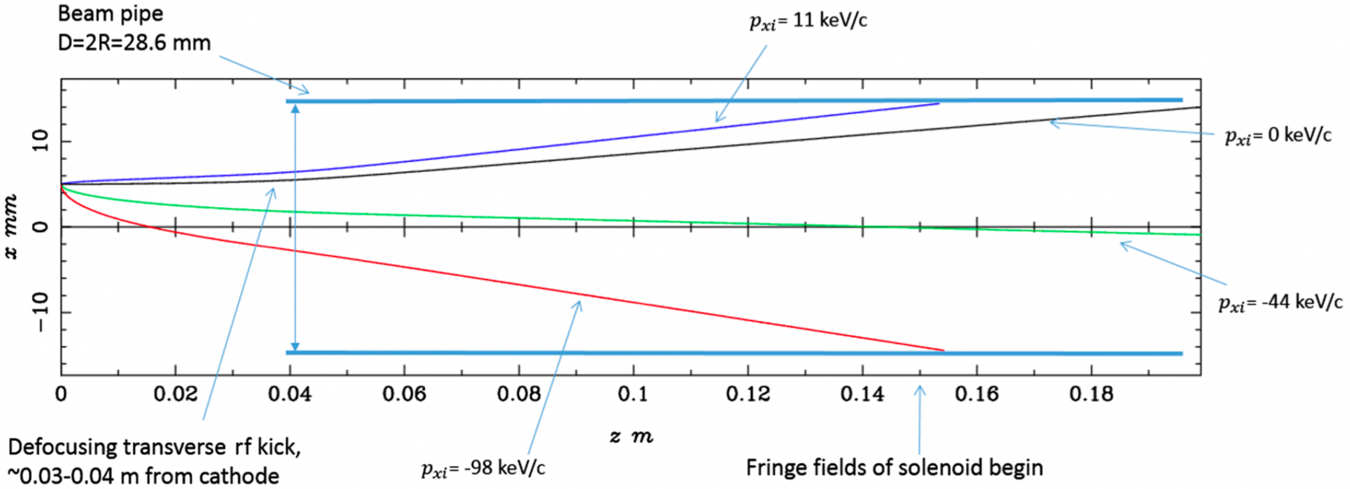




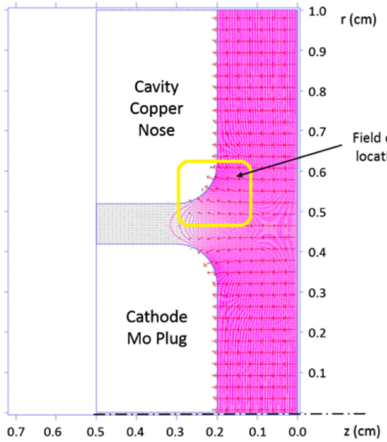
D. Filippetto, et al., Applied Physics Letters **107**, 042104 (2015).

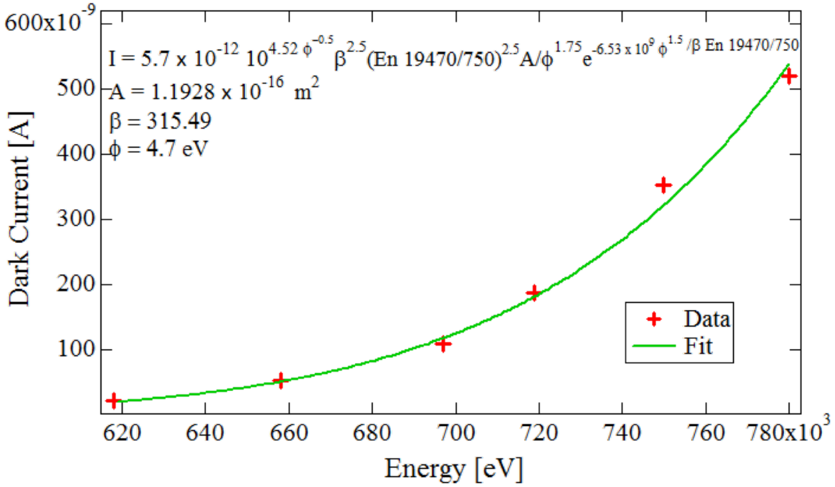
Dark Current generation and propagation

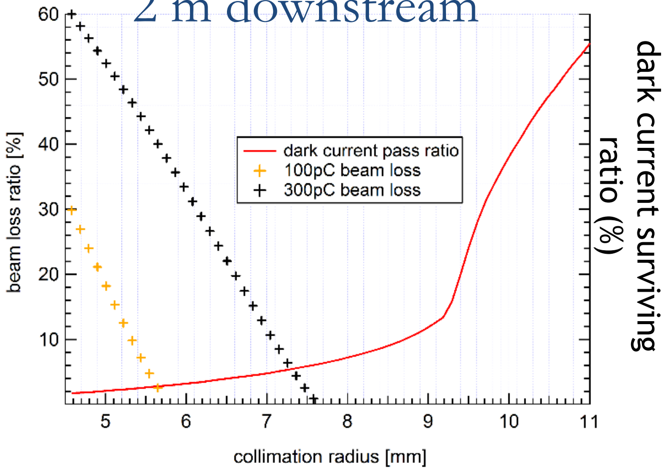




Passive collimation
2 m downstream

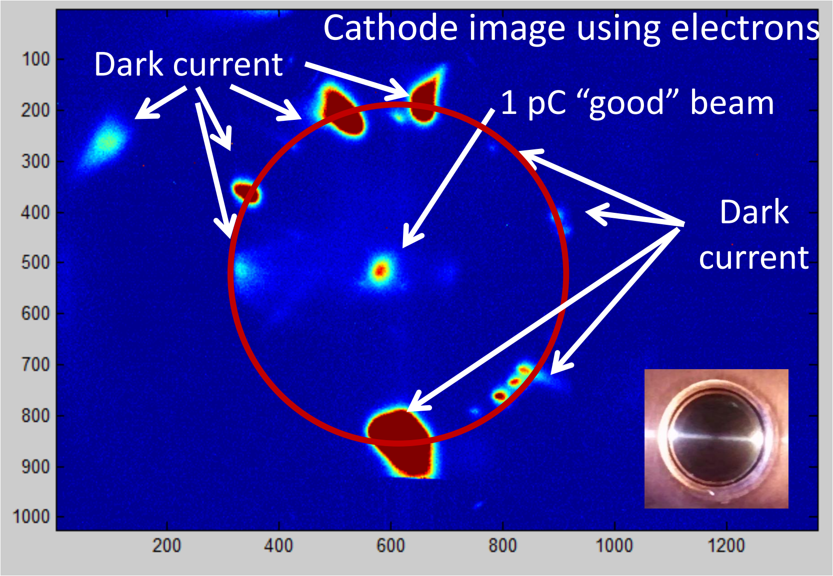


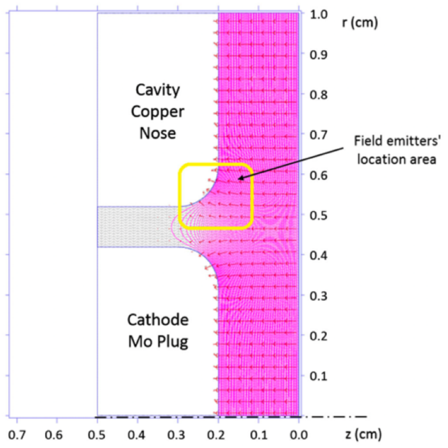




R. Huang, D. Filippetto, et al., PRSTAB **18**, (2015).

Dark Current generation and propagation

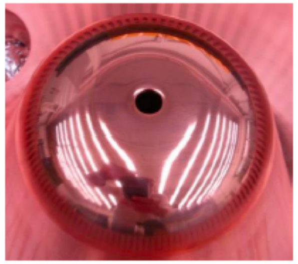




R. Huang, D. Filippetto, et al., PRSTAB **18**, (2015).

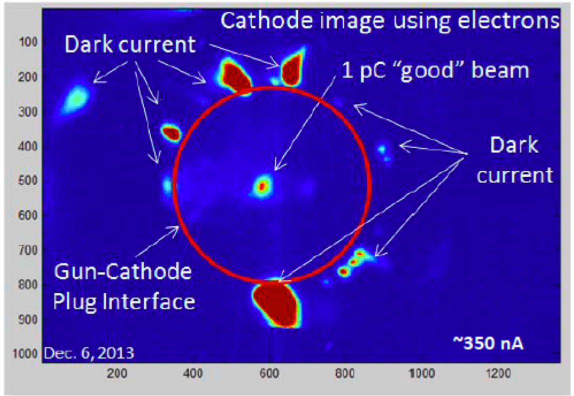
Combination of dry-ice cleaning and mirror-like polishing of the cathode/anode areas.

Dark current @ the nominal energy (750 keV) dropped from 350 nA to ~ 0.1 nA!

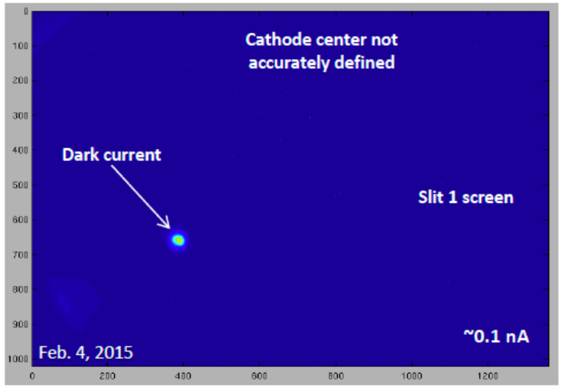


Combination of dry-ice cleaning and mirror polishing of the cathode/anode areas:

Dark current @ the nominal energy (750 keV) dropped from 350 nA to < 0.1 nA!



BEFORE

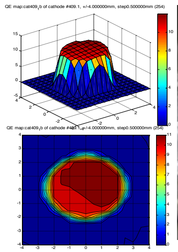


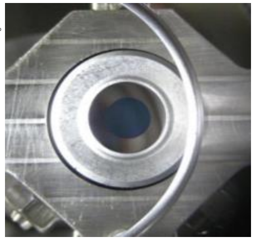
AFTER

HiRES operations with multi-alkali photocathodes

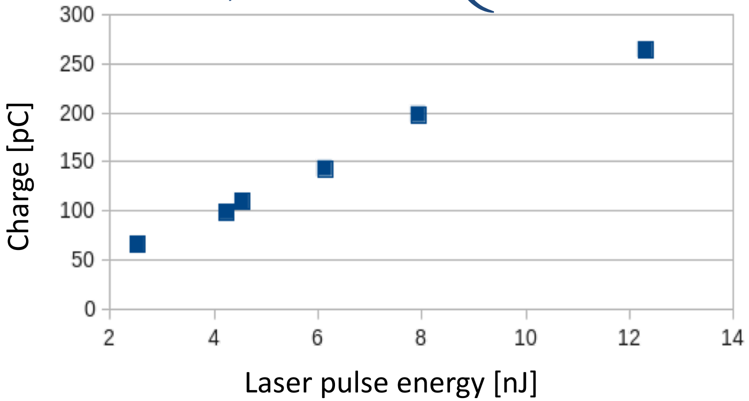
K_2CsSb cathodes (Padmore's group) have been used in the gun for over 3 years.

The last cathode has been in the gun since June 2017 and we are now measuring QE=4e-4 at 515nm

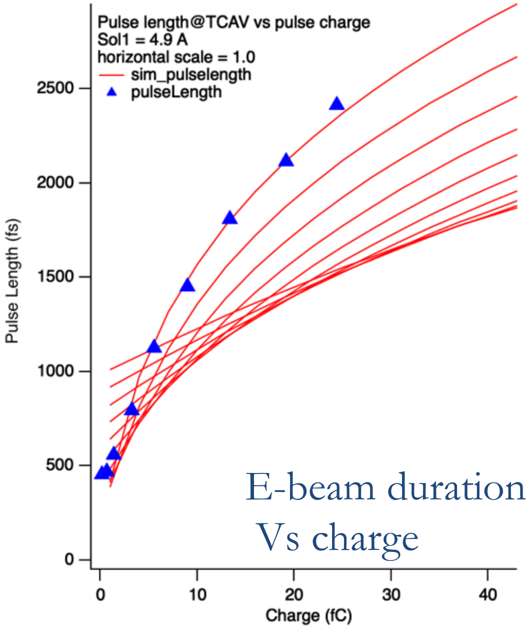




6% Initial QE



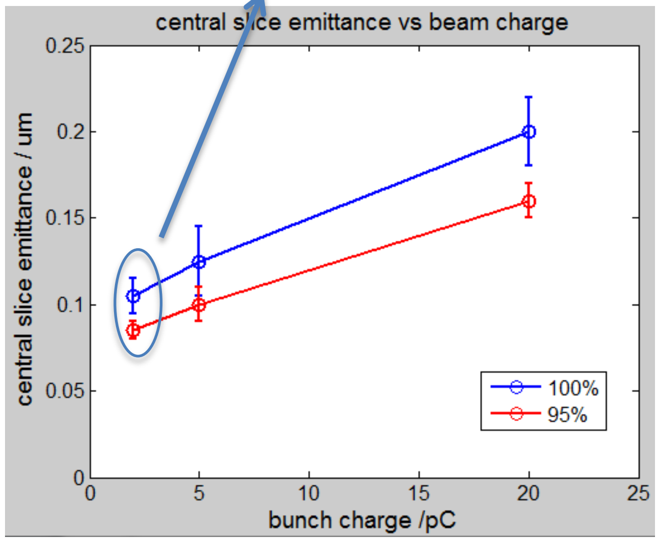
Prompt response



E-beam duration
Vs charge

100% slice over 100% laser rms
0.64 +/- 0.05 um/mm

95% slice over 95% laser rms
0.55 +/- 0.05 um/mm

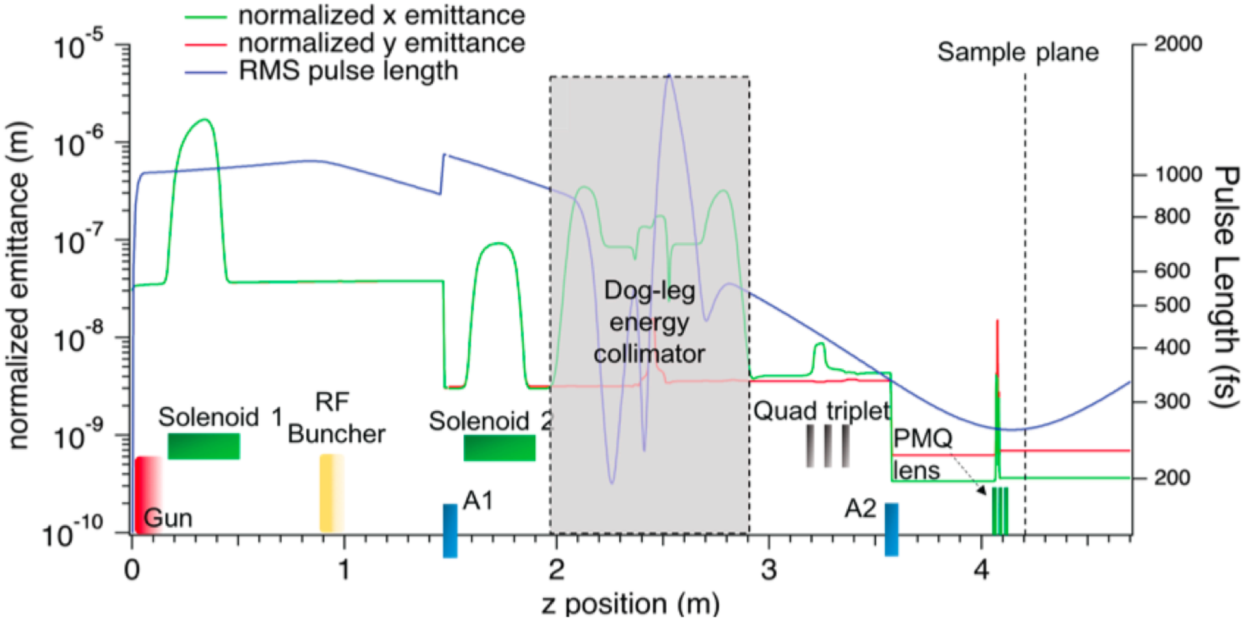


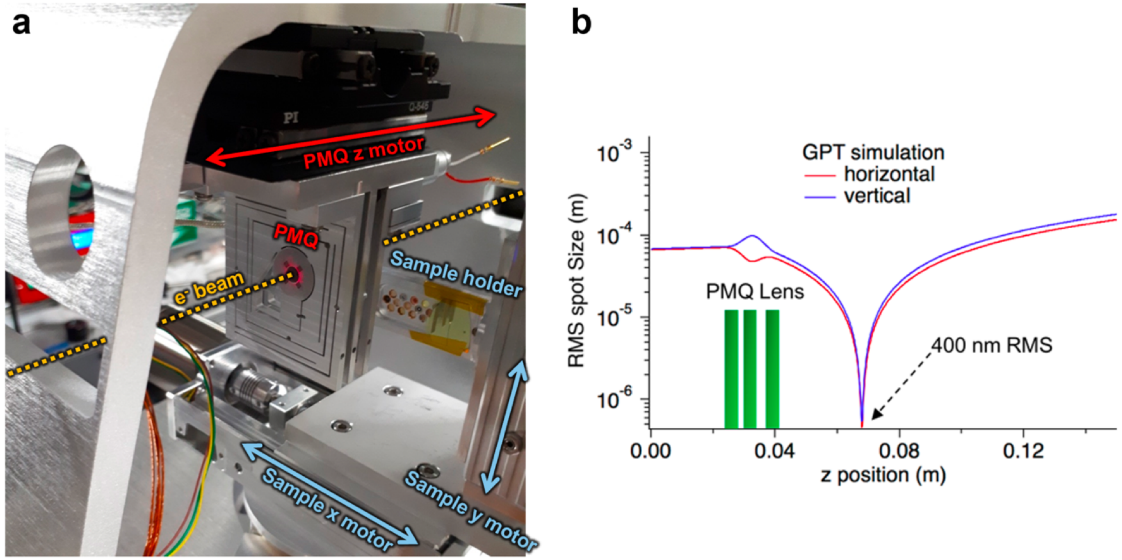
Generation of nanoscale electron beams for applications

The high electron flux of the source can be traded for emittance

Emittance is conserved during compression and transport through the dogleg

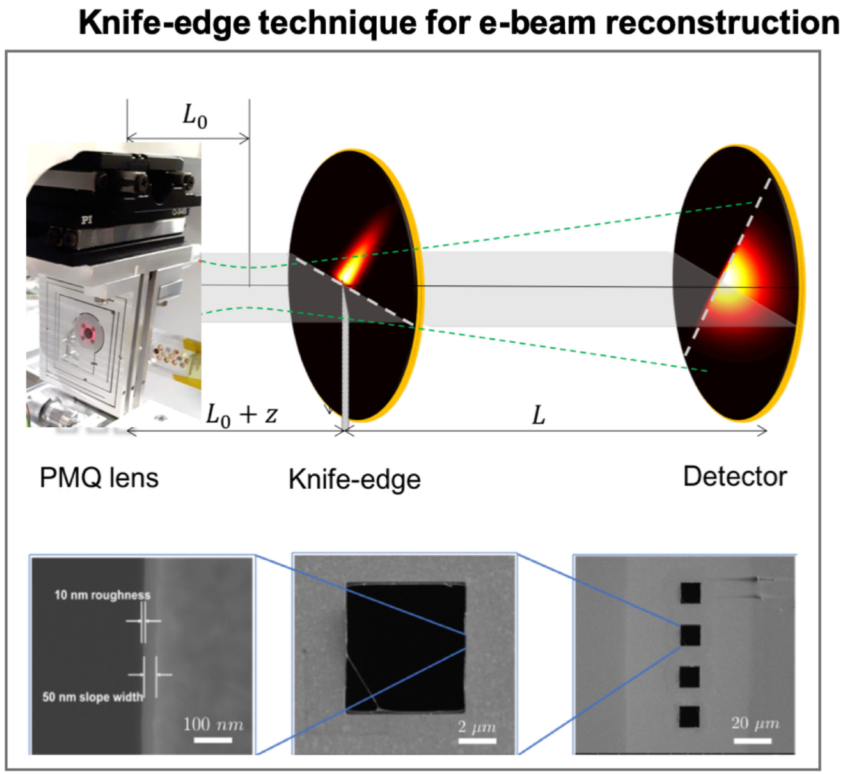
Permanent magnet quad triplet is used as final focus with f = 3 cm





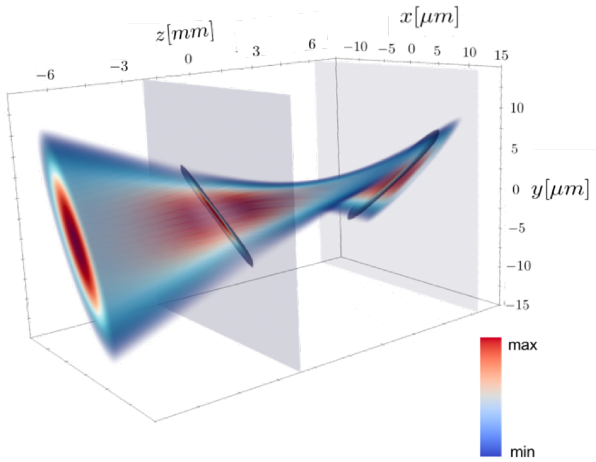
Measurement and applications of nanobeams with picometer-scale emittance

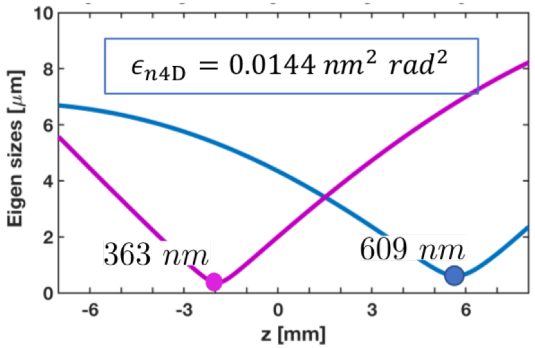
Focusing and measuring nanobeams



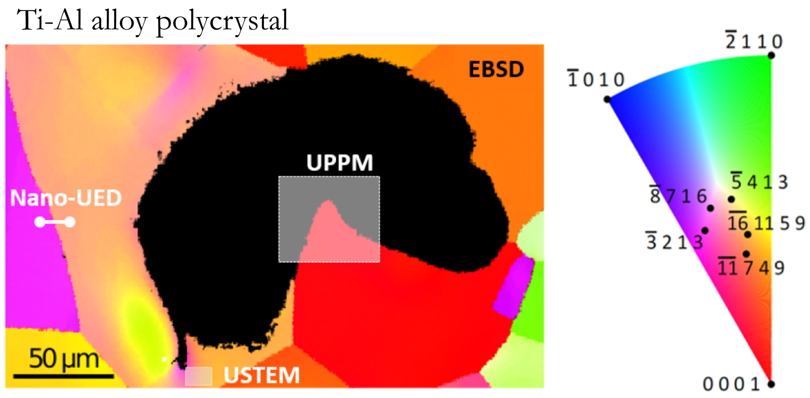
F. Ji, et al.,PRAB (22) 2019

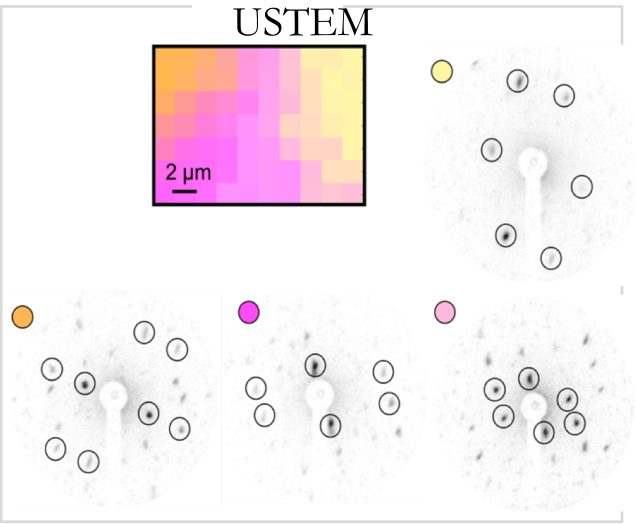
Reconstruction of the beam evolution





Flux and emittance demonstration

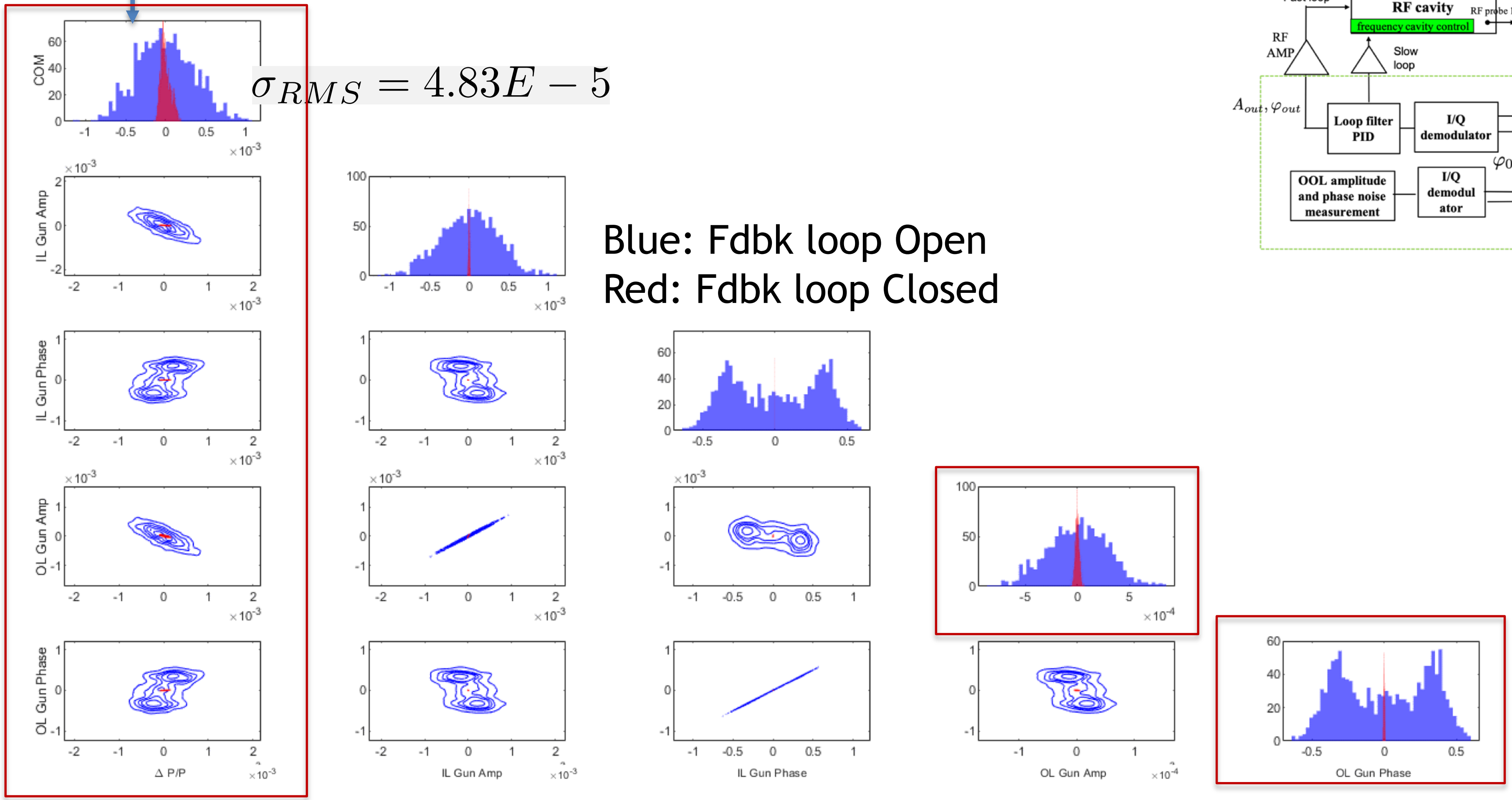




F. Ji, et al., Comm. Phys. 2 (54) 2019

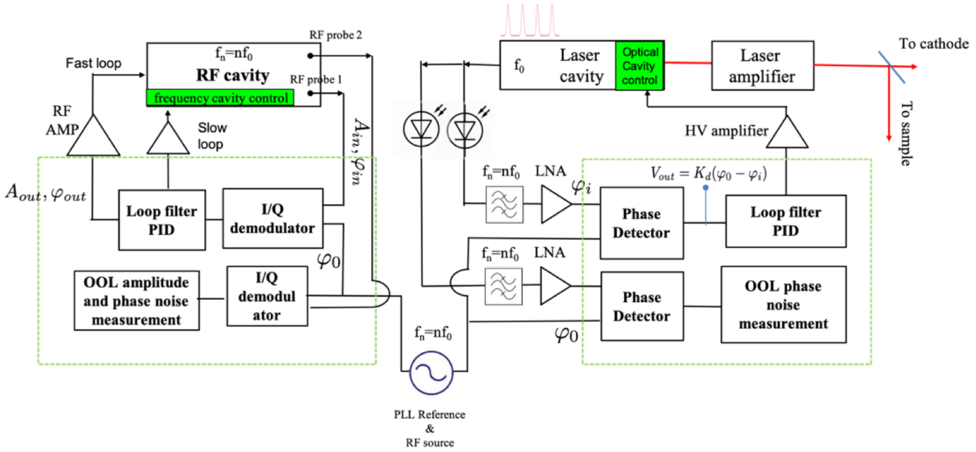
Development of low noise RF controls and their impact on the beam characteristics

Measured beam energy stability

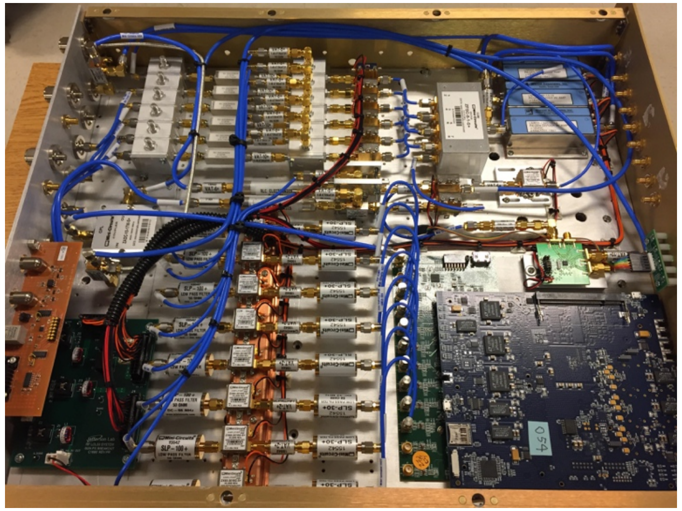


$$\sigma_{RMS} = 4.83E-5$$

Blue: Fdbk loop Open
Red: Fdbk loop Closed



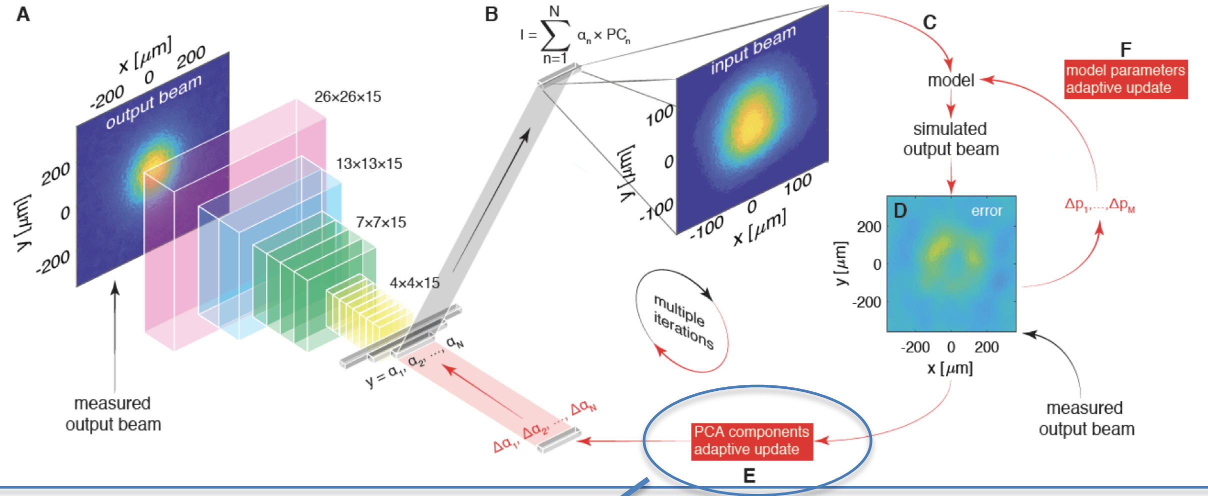
Ultra-low noise electronics



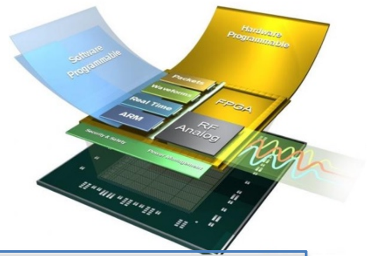
Machine Learning for particle accelerators: Advanced adaptive controls for enhanced stability

A. Scheinker, F. Cropp, S. Paiagua, and D. Filippetto, Sci Rep **11**, 19187 (2021).

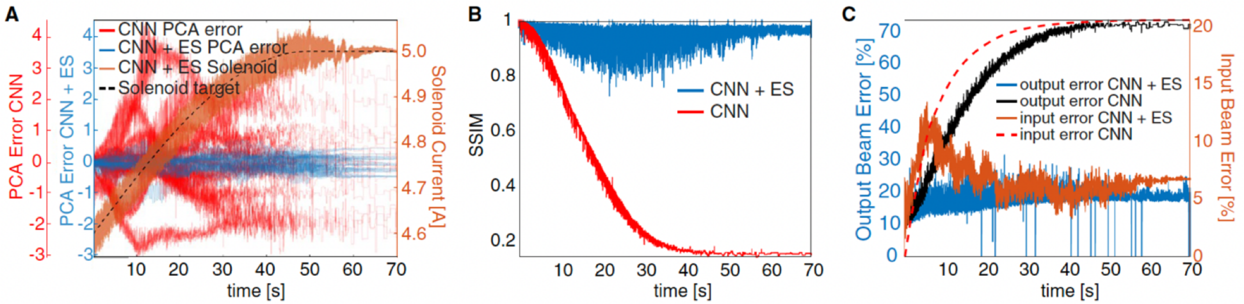
Schematic of a ML-based adaptive approach for time-varying systems, using inverse-models.



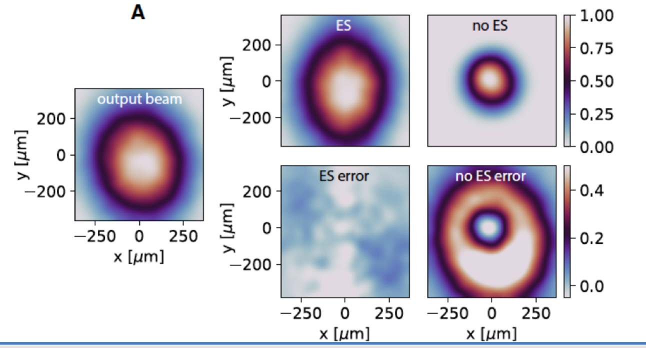
- Autoencoder algorithm strongly decrease number of variables (latent space)
- **Adaptive tuning using physics models allow to extend the CNN validity outside the training region.**
- Able to discriminate between different drifting components



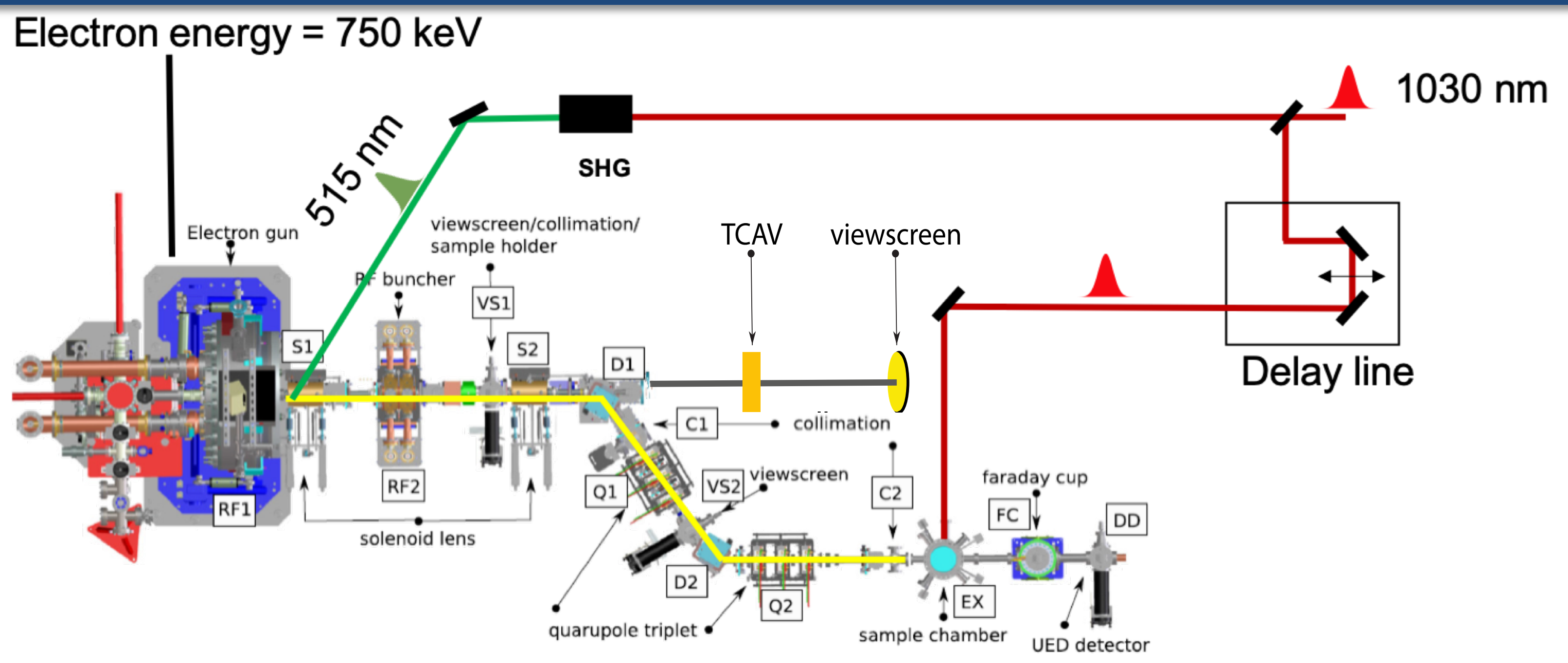
Adaptive loop (extremum seeking, ES) tracks changing parameters over time (focusing strength, laser initial distribution,…)



Comparison with target known distribution.
Error minimized using adaptive loop



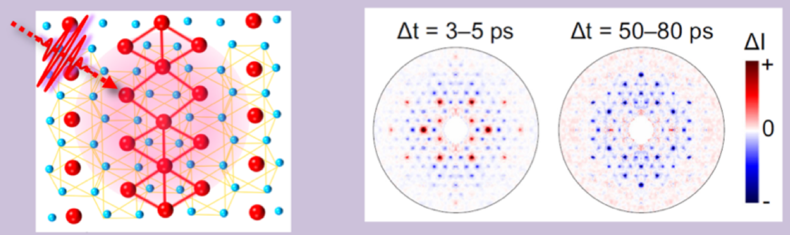
UED research directions at HiRES



Electron beam energy	**700-900 keV**
Repetition rate	**1-10^6 Hz**
Temporal resolution	**300 fs-1000 ps**
Electrons per pulse	**1-10^8**
Max Laser Fluence @ 1030nm	**1J/cm^2**
Spot at sample	**>50 µm**

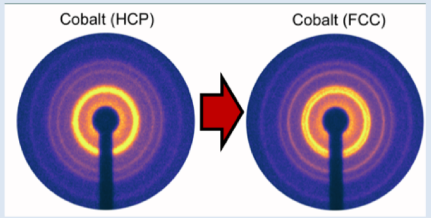
Quantum materials

Cryogenic trimer ordering in $TaTe_2$



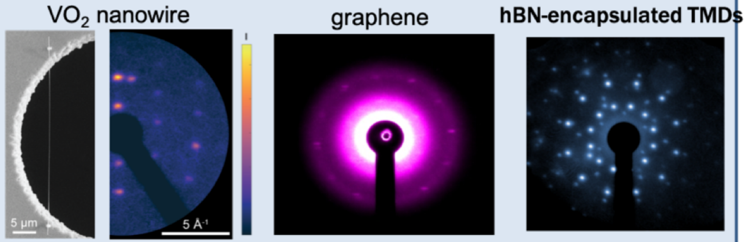
K.M. Siddiqui & D.B. Durham et al. *Commun. Phys.* **2021.**

Metals and alloys



*With A. Schmid (LBNL)

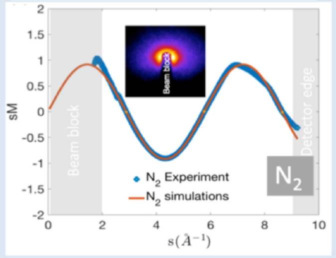
Low-dimensional materials



*With Lei Jin & Junqiao Wu (UCB)

*With J.D. Carlström & A. Raja (LBNL)

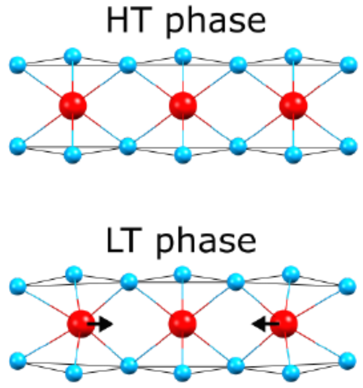
Gas-phase molecular

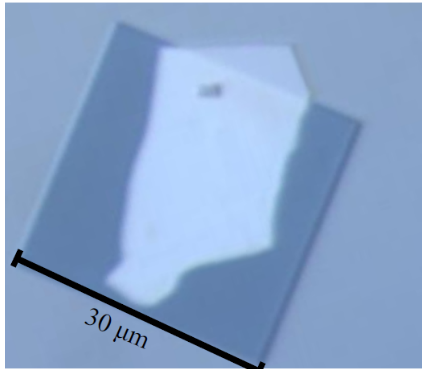


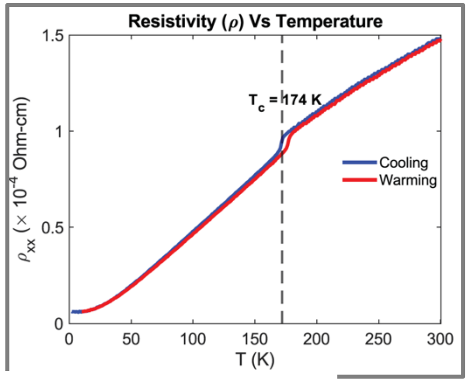
*With M. Centurion & X. Wang (UNR), D. Slaughter (CSD/LBNL)

UED unveils ultrafast dynamics during phase changes in new quantum materials: 1T'-$TaTe_2$

In-layer trimer clusters form at low temperature

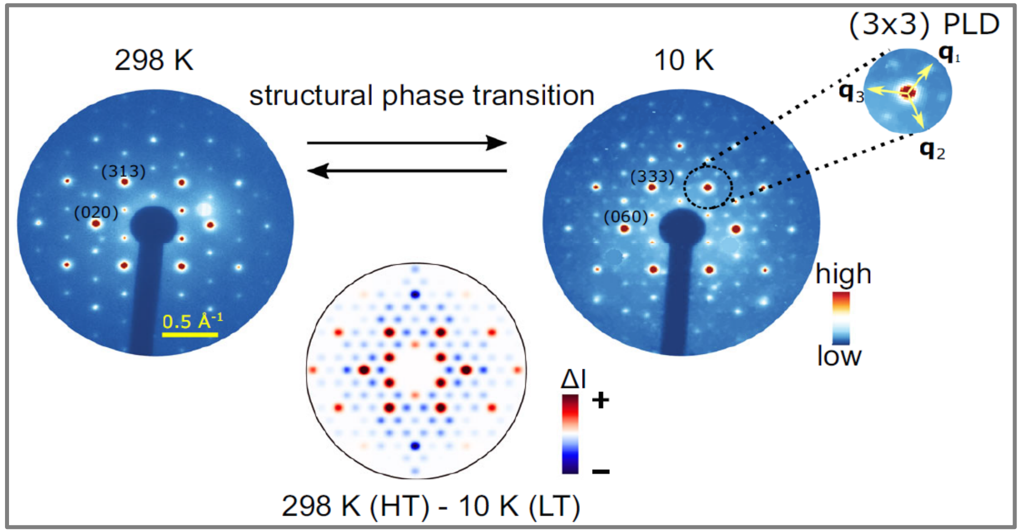




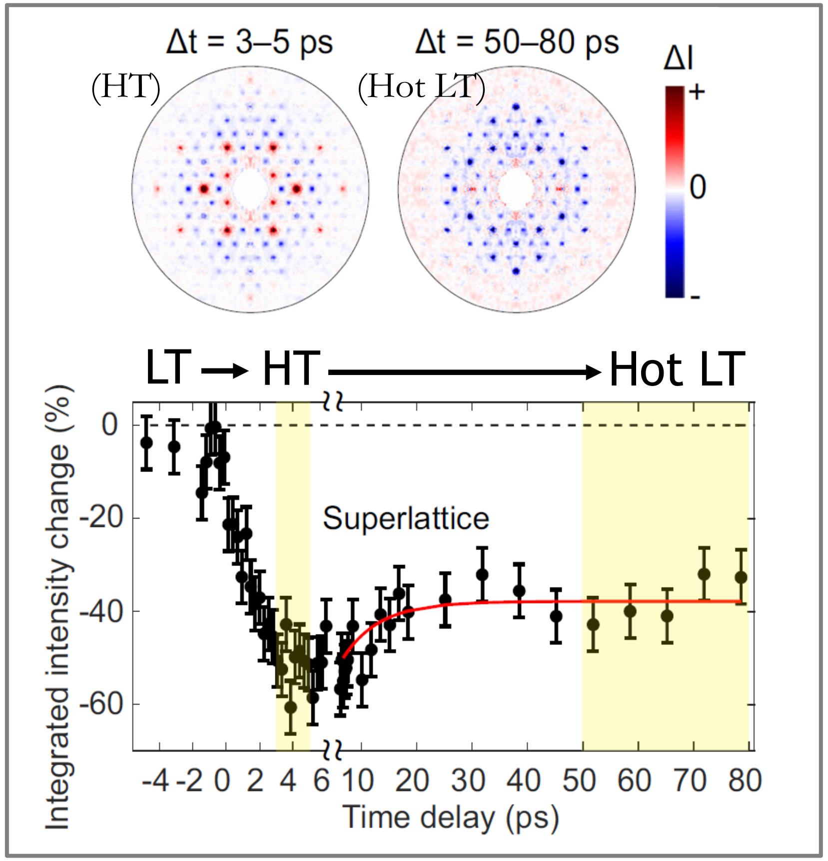


*from Y. Zhu and Z. Mao at PSU

Emergence of superlattice peaks at low temperature



Recovery to a heated trimer structure within 20 ps



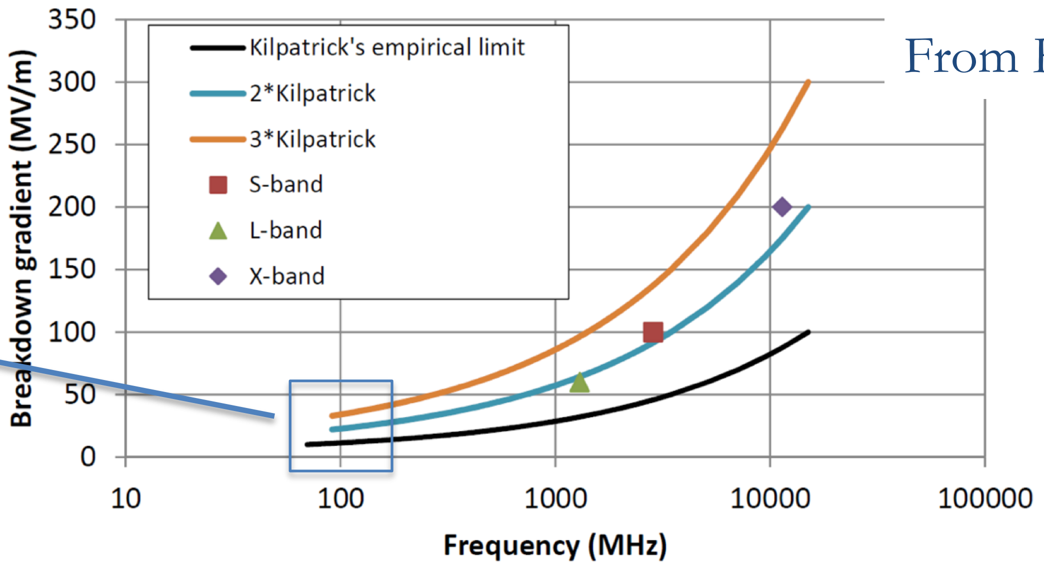
K.M. Siddiqui & D.B.Durham et al. *Commun. Phys.*, **2021**

Large unexplored parameter space in performance and applications

NCRF CW technology has room for improvements

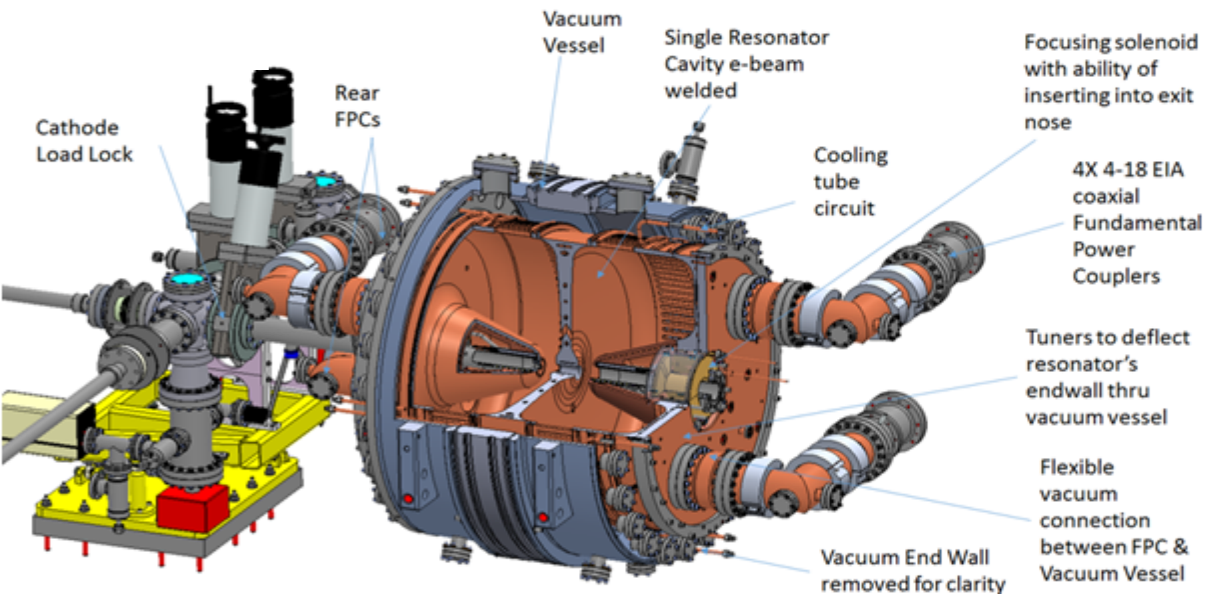
- APEX gun was designed with a conservative nominal accelerating field values.
- Experience from continued operations (since 2012) suggests large room for improvements (no RF breakdown events).
- Electron gun accelerating field is limited by available RF power, not by power density or RF breakdown
- The second-generation of NCRF CW guns has not been fabricated yet, differently from other gun technologies (DC, SRF, GHz-NCRF)

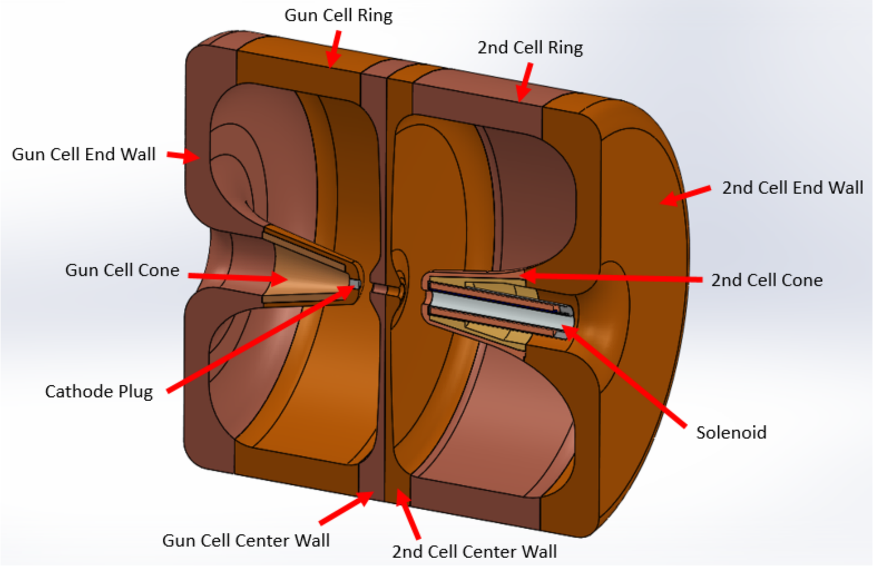
@ 200MHz
$2E_k$=30MV/m



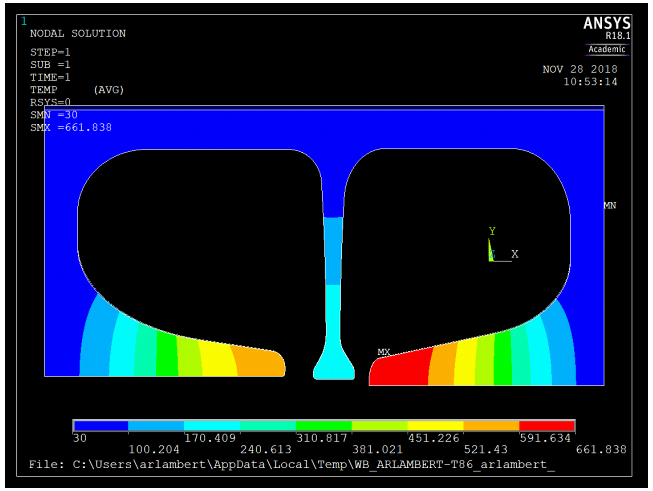
From H. Qian

Next-generation APEX: APEX-II



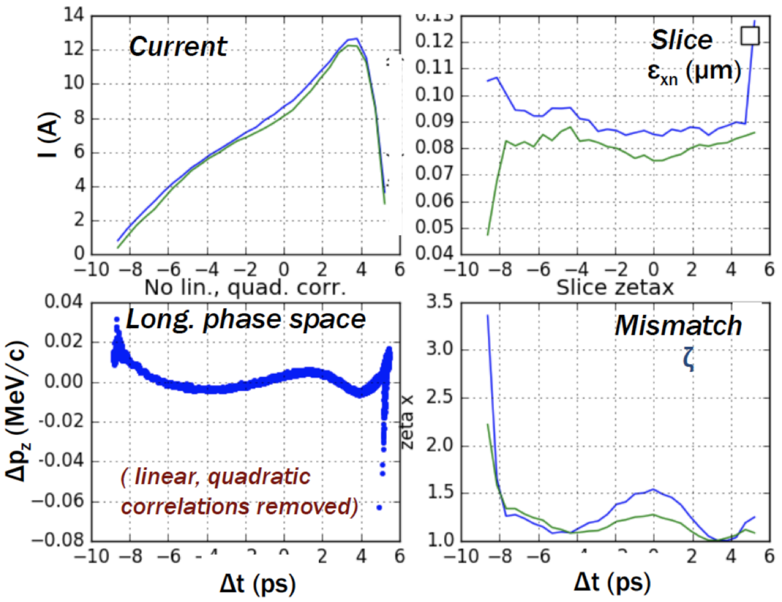


	APEX gun	APEX-2 gun Cell 1	APEX-2 gun Cell 2	
Frequency	185.7	162.5	162.5	MHz
Peak acceleration field	19.5	34	25	MV/m
Gun voltage	750	820	820	kV
Average RF power	90	91	85	kW
Shunt impedance	6.3	7.3	7.8	Mohm
Peak surface field	24.1	37	25	MV/m
Peak thermal power density	25	32	30	W/cm^2
Diameter/Length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

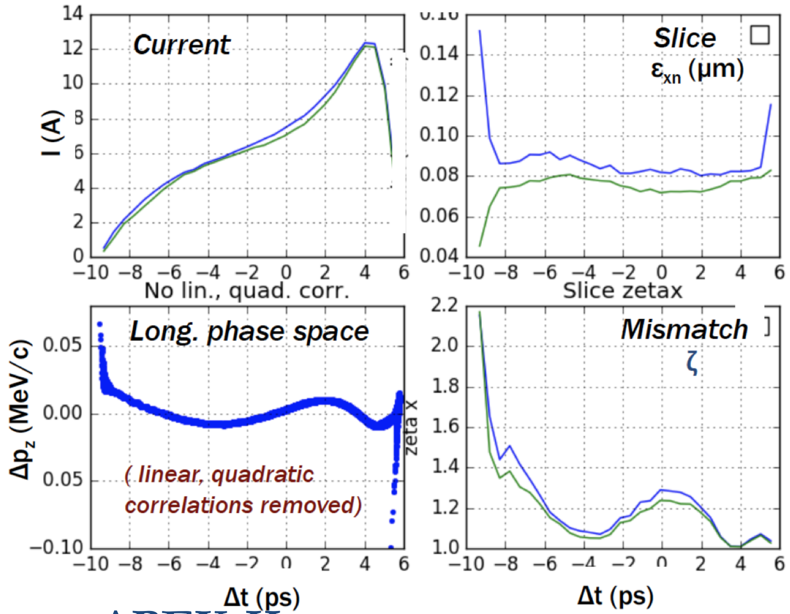


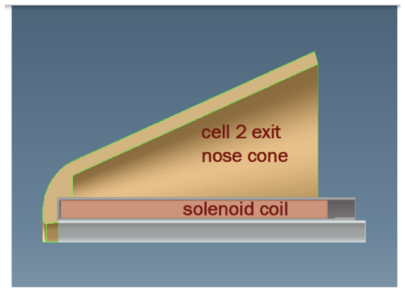
Emittance and peak current performance at 100 MeV

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

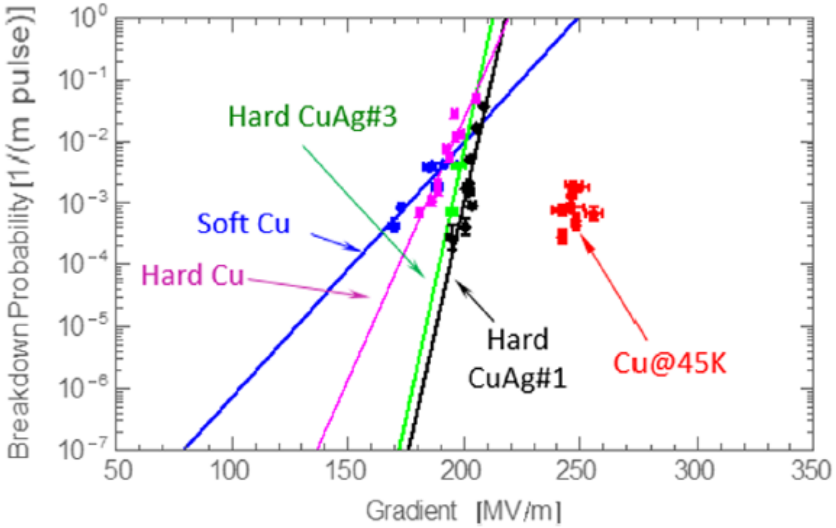
Parameter	30 MV/m	35 MV/m
ε_{xn} (100%) [μm]	0.1033	0.0968
ε_{xn} (95%) [μm]	0.0897	0.0839
Peak current [A]	12.0	12.0
KE [MeV]	115	124
HOM* [keV/c]	3.66	6.63

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

Future opportunities for upgrade

A. D. Cahill, et al., Phys. Rev. Accel. Beams **21**, 102002 (2018).

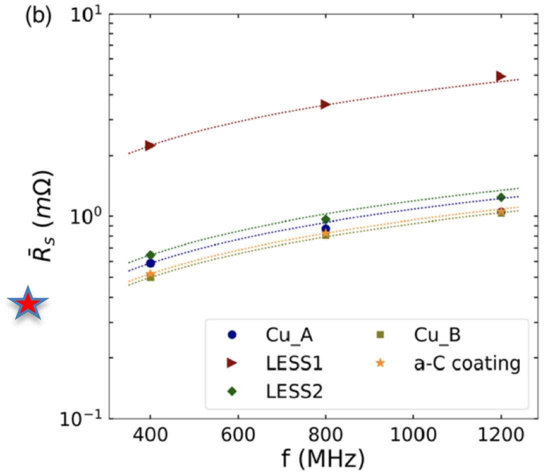


Anomalous skin effect leads to a decrease of Surface resistance with temperature

At 186 MHz

R_s= 0.38 mΩ @ 4 K
0.75 mΩ @ 80 K
3.5 mΩ @ 270 K

S. Calatroni, et al., PRAB **22**, 063101 (2019).



As the temperature of copper decreases:

- Thermal conductivity of the copper increases
- Surface resistance increases, raising Q_0
- Suitable convective heat transfer rates are achievable with flowing liquid nitrogen
- LN has only 25% of the specific heat capacity of water-> high flow rates
- The optimum cooling channel geometry (size, spacing, length) will not be the same as with water cooling.

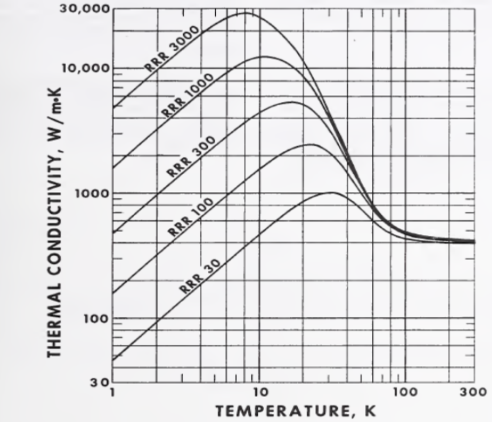


Figure 7.4. Thermal conductivity for C10100–C10700 copper is shown as a function of temperature calculated from Equation (7-2) at selected values of the RRR. This figure is adapted from a figure presented in Reference 7.20.

Conclusions

- The Normal Conducting CW RF gun has demonstrated its design parameters
- It is a mature technology, with a large room for improvements
- Modifications of the shape and/or cooling and/or fabrication procedure of the gun would likely lead to accelerating values in excess of 30 MV/m, with increase in Q requiring similar RF power.

- The technology is presently used to drive large scale BES facilities (LCLS-II) and to generate short beams for UED experiments
- The R&D at HiRES is highly synergistic with HEP-relevant requirements
  - mA-scale average currents
  - Vacuum levels
  - Nanobeam technology

The team

K. Baptiste, M. Chin, J. Corlett, C. Cork, E. Cropp, S. De Santis, L. Doolittle, J. Doyle, D. Durham, D. Filippetto, G. Harris, G. Huang, H. Huang, R. Huang, F. Ji, T. Kramasz, S. Kwiatkowski, R. Lellinger, C. Mitchell, V. Moroz, W. E. Norum, C. Papadopoulos, G. Portmann, H. Qian, F. Sannibale, J. Staples, K. Siddiqui, M. Vinco, S. Virostek, W. Wan, R. Wells, M. Zolotorev,