FACET-II | Facility for Advanced Accelerator Experimental Tests

Advanced Accelerator Concepts and Facilities – Laser cleaning now while planning for colliders of the future

11-NOV–2021

Mark J. Hogan
Senior Staff Scientist
FACET & Test Facilities
Division Director

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

On a Personal Note: It's Exciting to Hear How Far Things Have Come and Many of the Themes Feel Familiar

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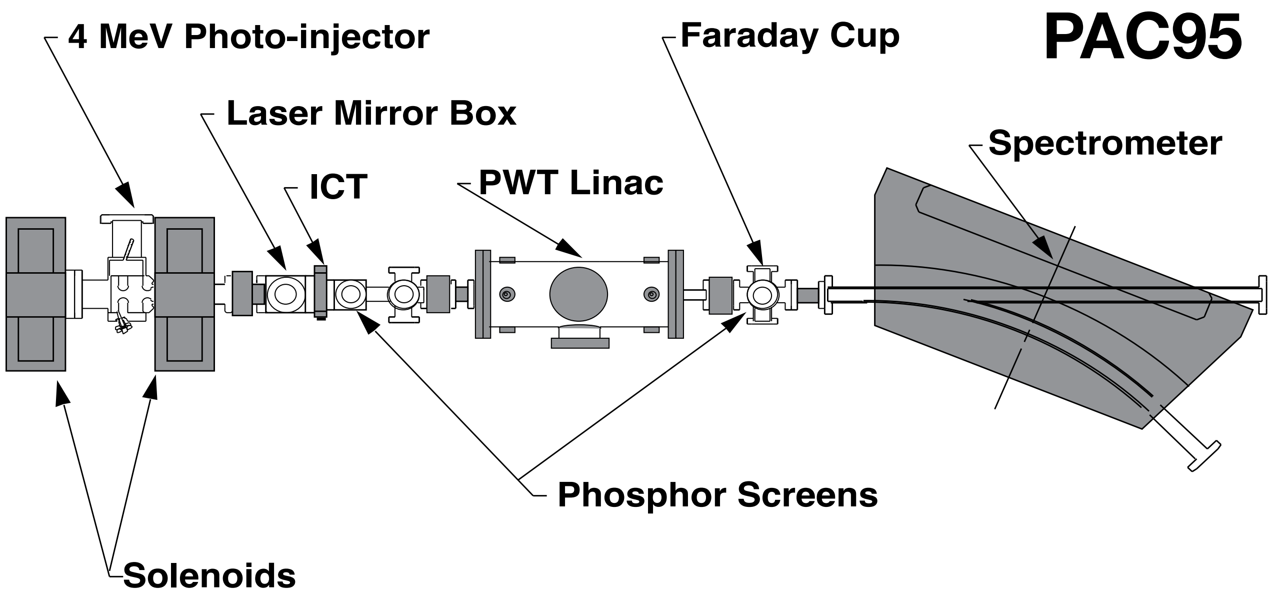
The UCLA Compact High Brightness Electron Accelerator

P. Davis, G. Hairapetian, M. Hogan, C. Joshi, M. Lampel, S. Park,
C. Pellegrini, J. Rosenzweig, G. Travish and R. Zhang

Departments of Physics and Electrical Engineering, University of California, Los Angeles 90024

PAC95



Beam uniformity, quality

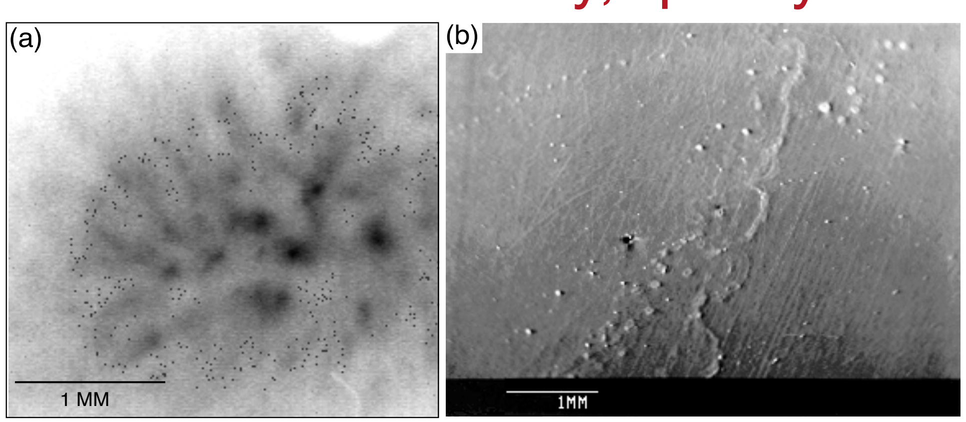


FIG. 5. Hand polished copper cathode. (a) Electron beam emission from the cathode surface. (b) SEM micrograph of cathode surface after running in the rf gun.

Dark current

Surface contamination

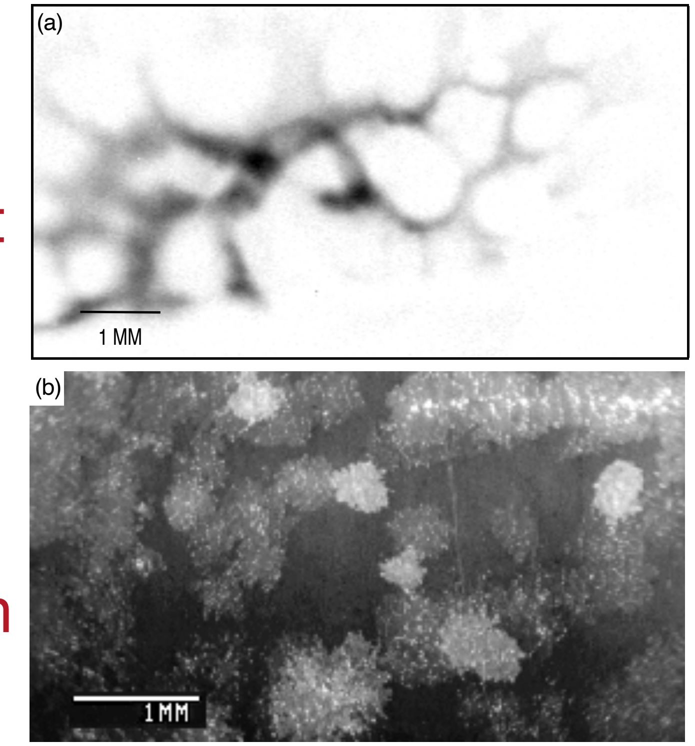


FIG. 3. Spawr Cathode images. (a) Electron beam emission from the cathode surface. (b) SEM micrograph of cathode surface after running in the rf gun.

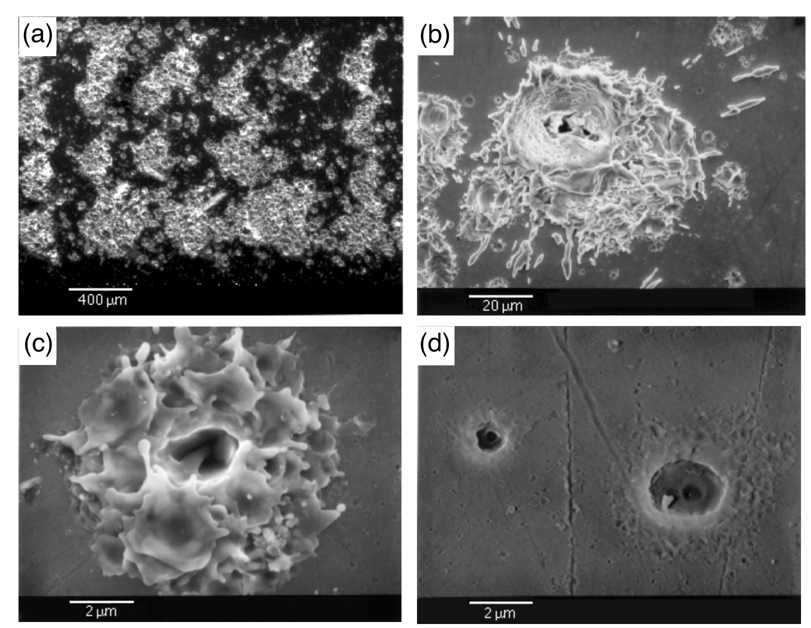


FIG. 4 SEM micrographs of damage on the Spawr cathode. (a) laser damaged region (b) laser produced crater (c) multiple rf breakdown produced crater (d) single rf breakdown crater

Laser cleaning
RF Breakdown

Outline

A story in three parts:

- Source requirements for beam driven plasma wakefield based collider concepts
- Beam driven plasma based high-brightness injectors
- Challenges operating FACET-II Photoinjector > nC/bunch

Great Desire for Access to High Energy Beams

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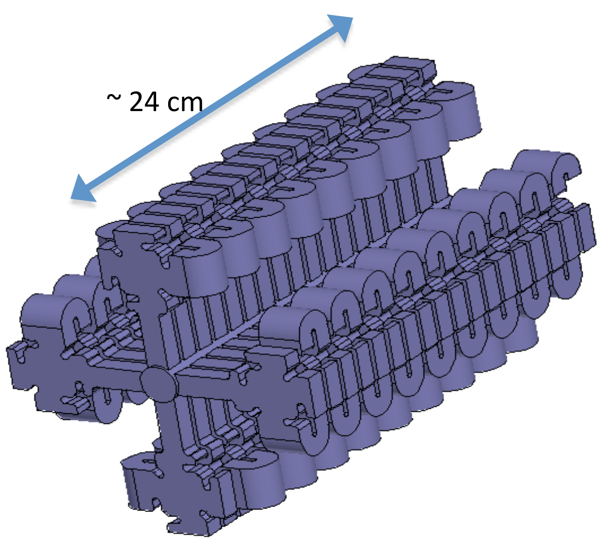
High energy particle accelerators are the ultimate microscopes

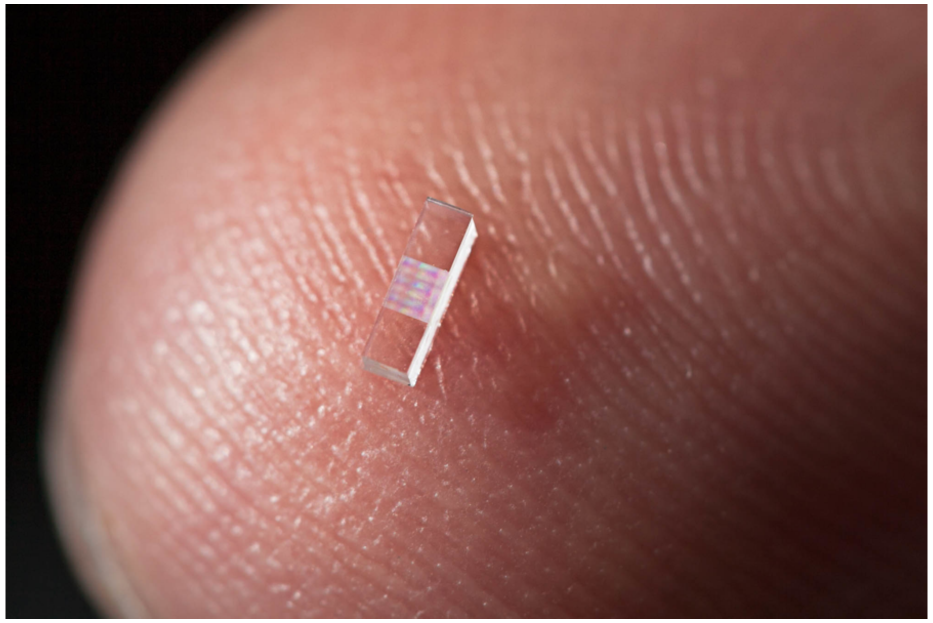
- Reveal fundamental particles and forces in the universe at the energy frontier
- Enable x-ray lasers to look at the smallest elements of life on the molecular level

~100MeV/m



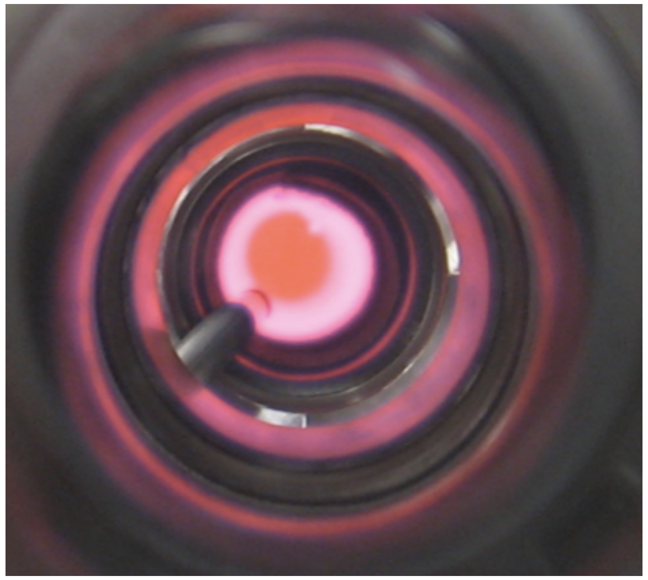
New designs and materials push metal structures to the limit

~1GeV/m



Telecom and Semiconductor tools used to make an 'accelerator on a chip'

~10GeV/m



Extremely high fields in plasmas have doubled the energy of the 3km SLAC linac in just 1 meter

Looking for advanced concepts to increase accelerator performance by factors of 10-1000

The Scale for a TeV Linear Collider

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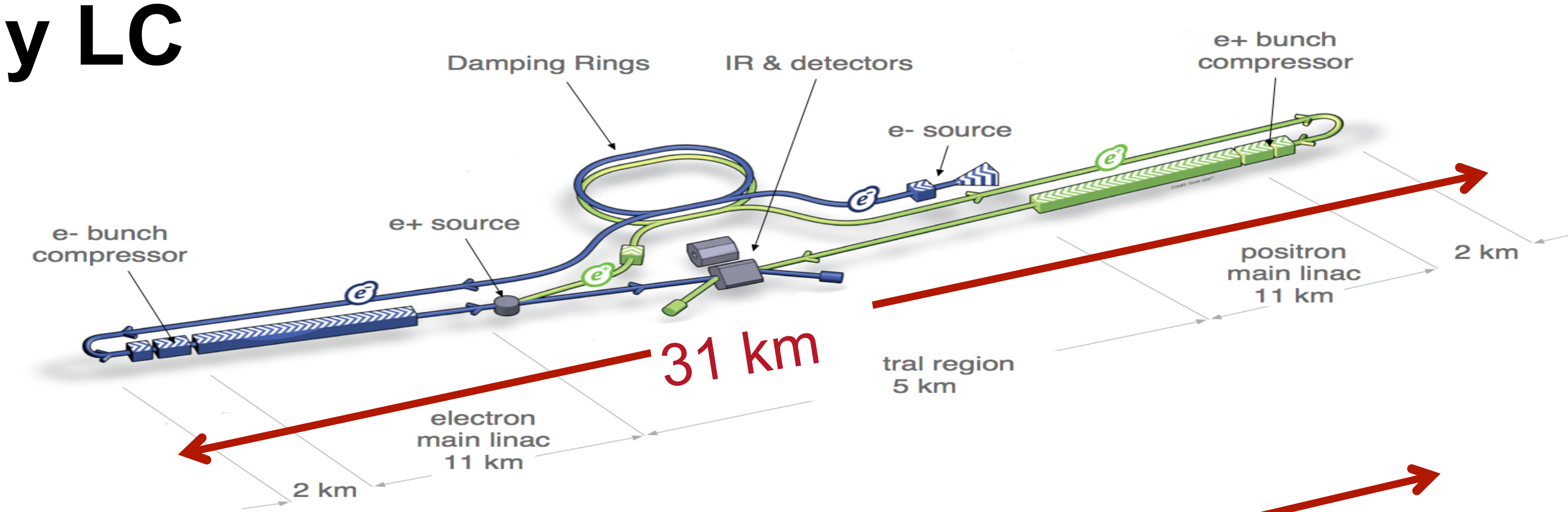
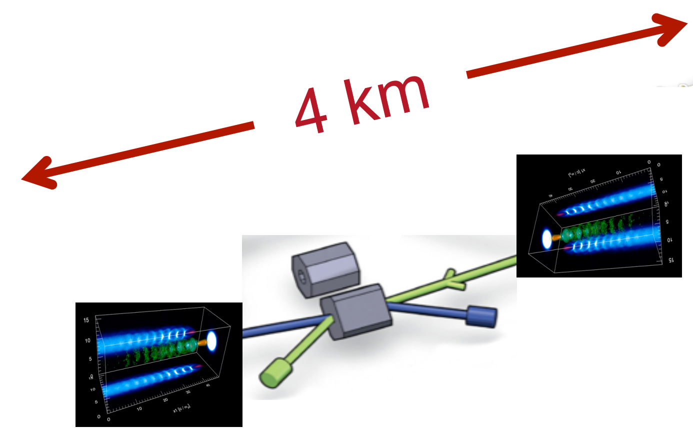
Today's technology LC – a 31km tunnel:



Advanced Accelerator Technology LC:



➡ GeV/m accelerating gradient

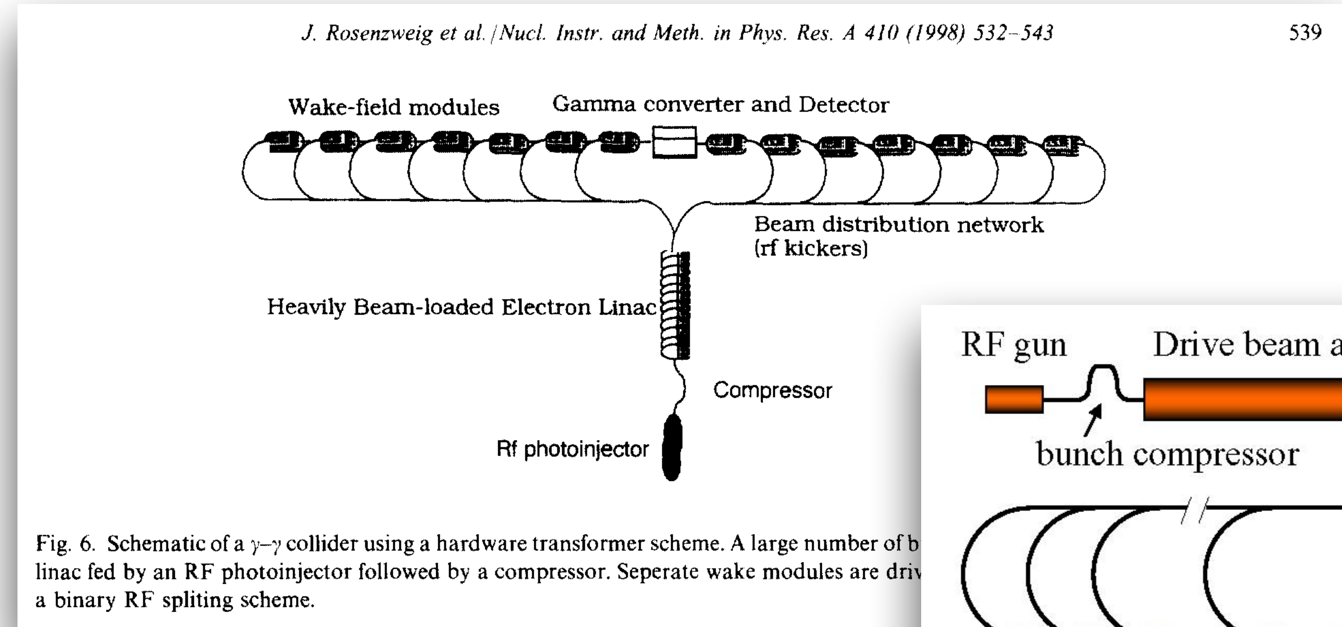
The Luminosity Challenge:

➡ High-efficiency

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

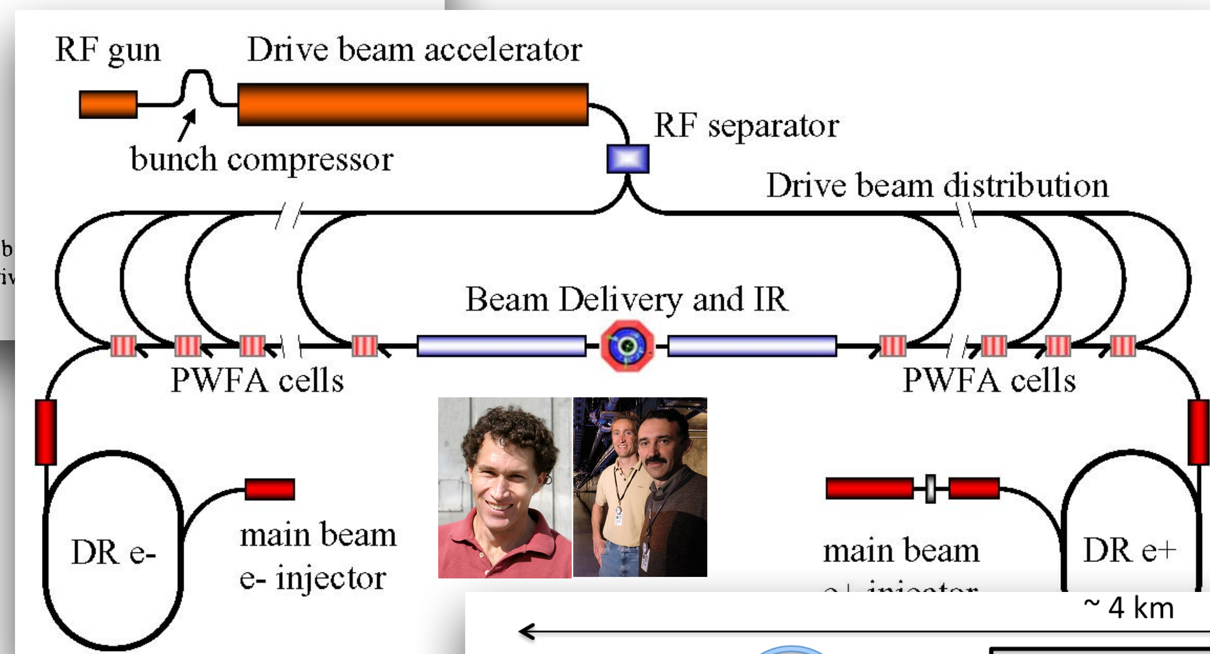
…and must do it for positrons too!

Beam Driven Plasma Accelerator Based Collider Concepts – Not CDR/TDRs, but Strawman Designs to Focus R&D Priorities



Rosenzweig *et al* (1998)

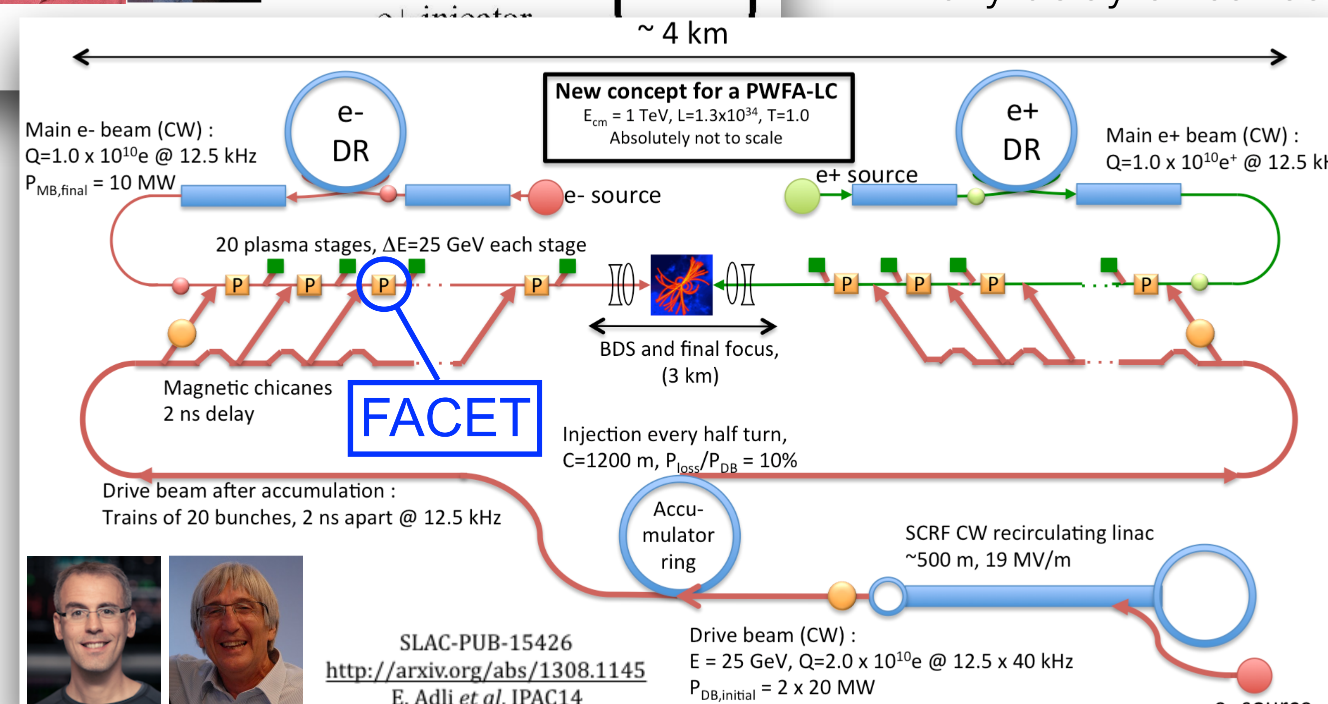
Seryi *et al* (2008) SLAC-PUB-13766



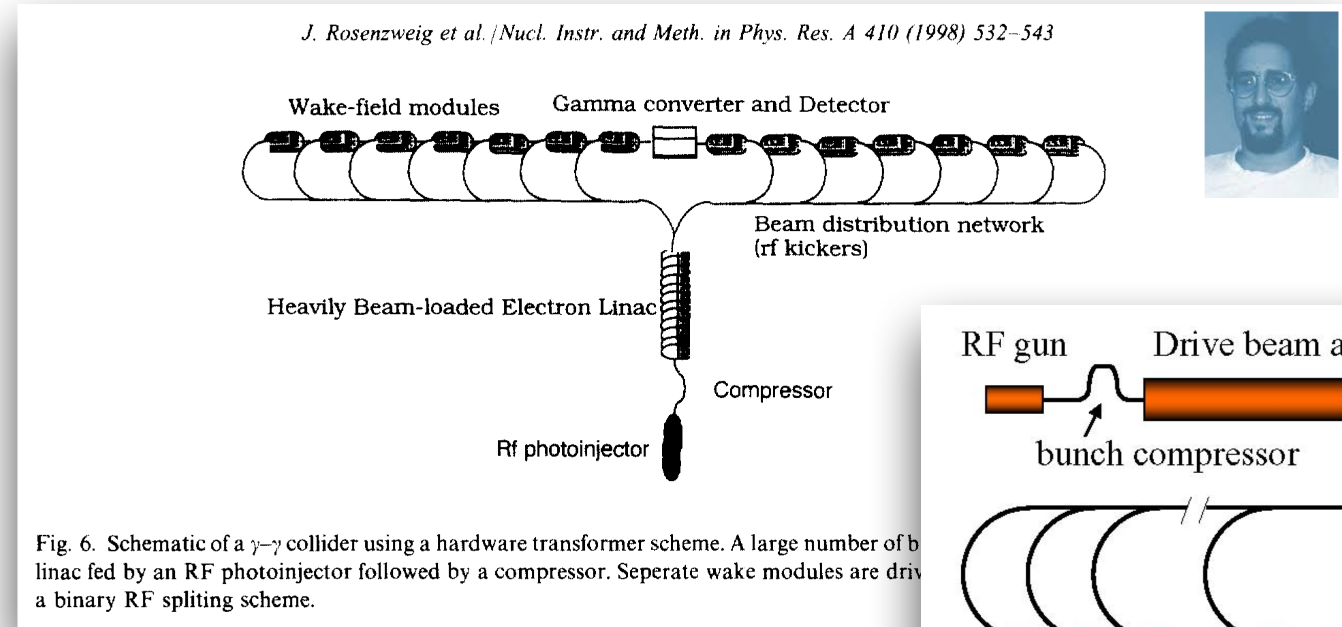
Adli *et al* (2013)
SLAC-PUB-15426

- 'Cold' Drive Linac
- 100μs bunch spacing
- Tricky delay chicanes

- Assume SLC/NLC/ILC/CLIC made smart choices that we can start from for main beam and driver
- Focus on the accelerator module itself (the plasma)
- **The plasma is a transformer**
- For luminosity – Power efficiency and beam quality are critical!



Beam Driven Plasma Accelerator Based Collider Concepts – Not CDR/TDRs, but Strawman Designs to Focus R&D Priorities



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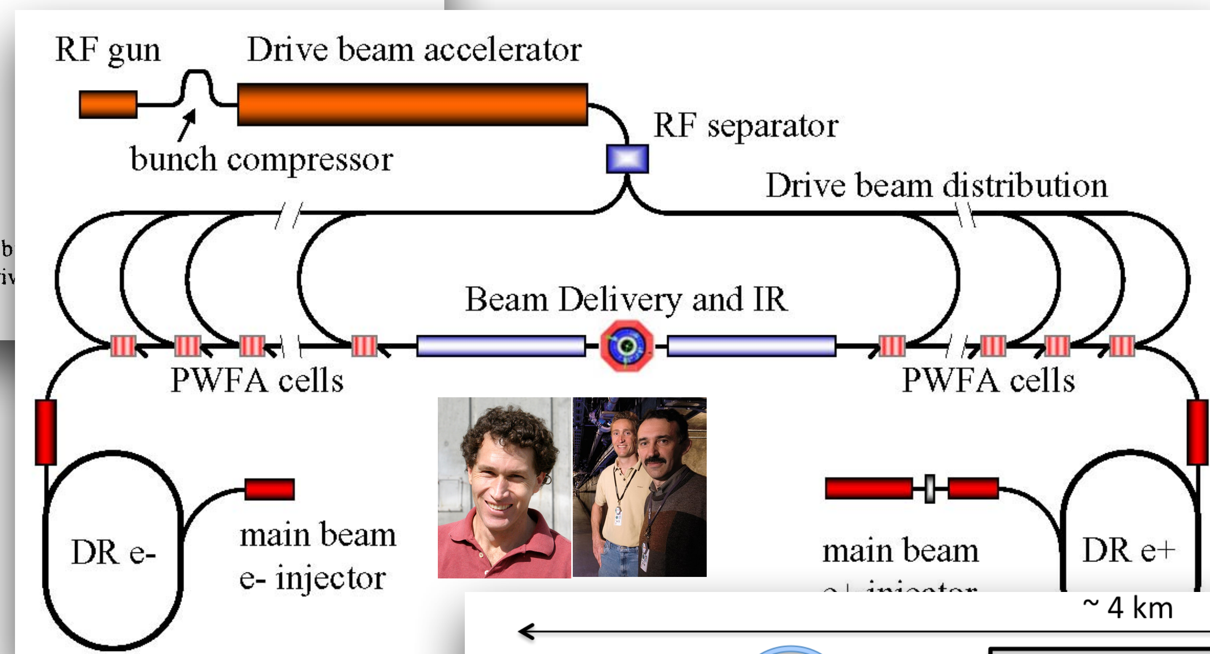

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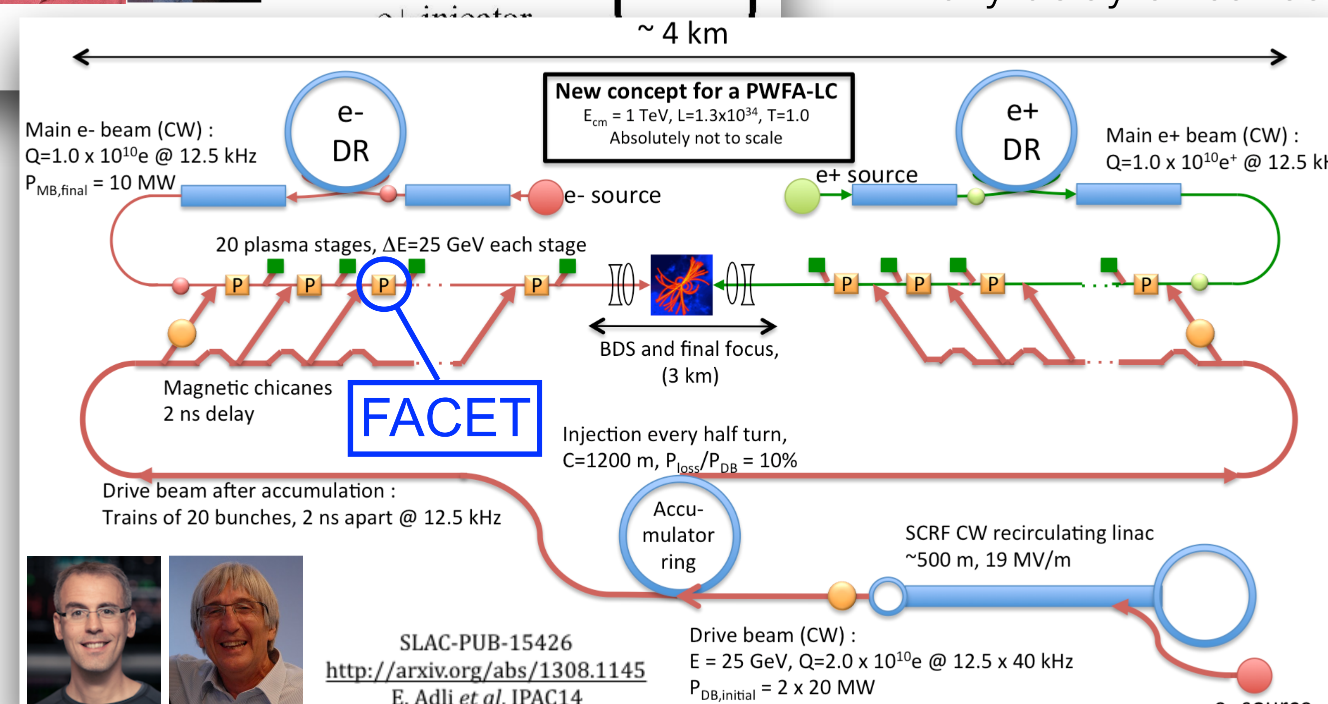

Assume SLC/NLC/ILC/CLIC Made Smart Choices That We Can Start From For Main Beam and Driver

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Normal Conducting PWFA-LC

- Drive: 3E10, 20 mini-trains, 250 bunches/train, 100 trains/sec
- Main: 1E10 (1.6nC)/bunch, 125 bunches/train, 100 trains/sec

Superconducting PWFA-LC

- Drive: 3E10, CW 300kHz to 1 MHz
- Main: 1E10, 10-30kHz

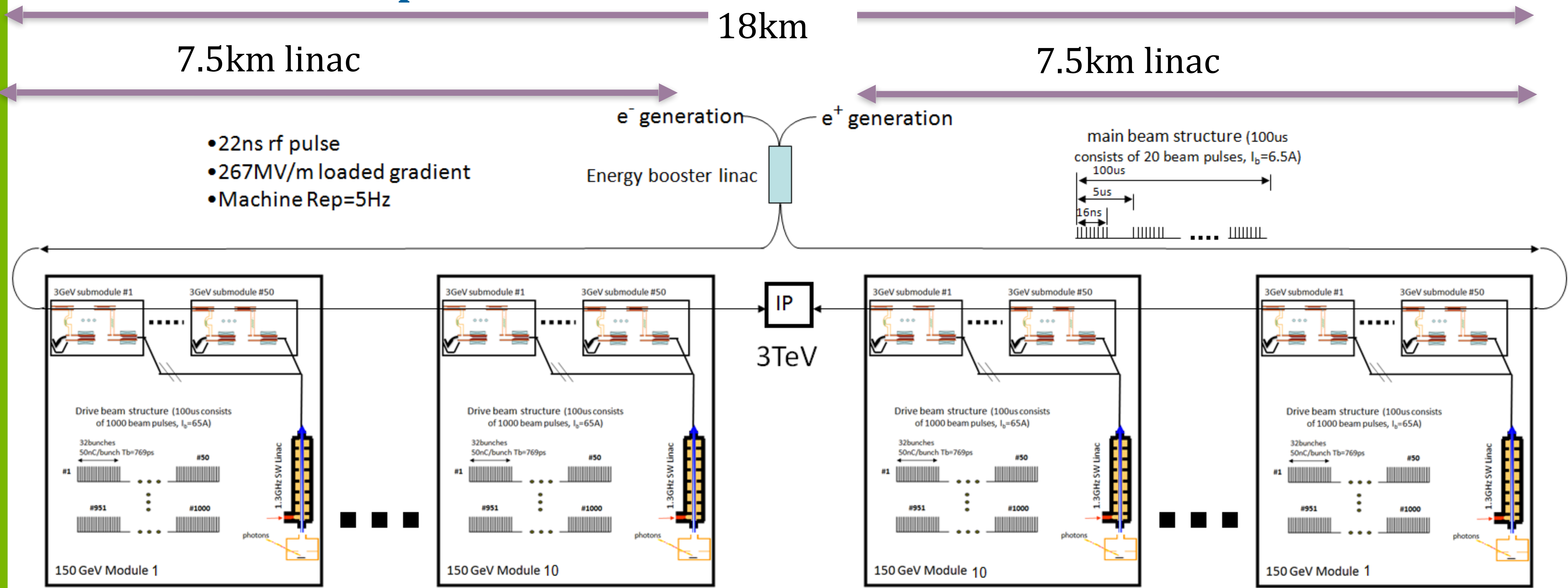
Assumptions

- Conventional linacs for drive beam energy ~25GeV
- Bunch compressors for peak current
- Drive beam 10’s μm emittance
- Main beam will require damping ring for low emittance

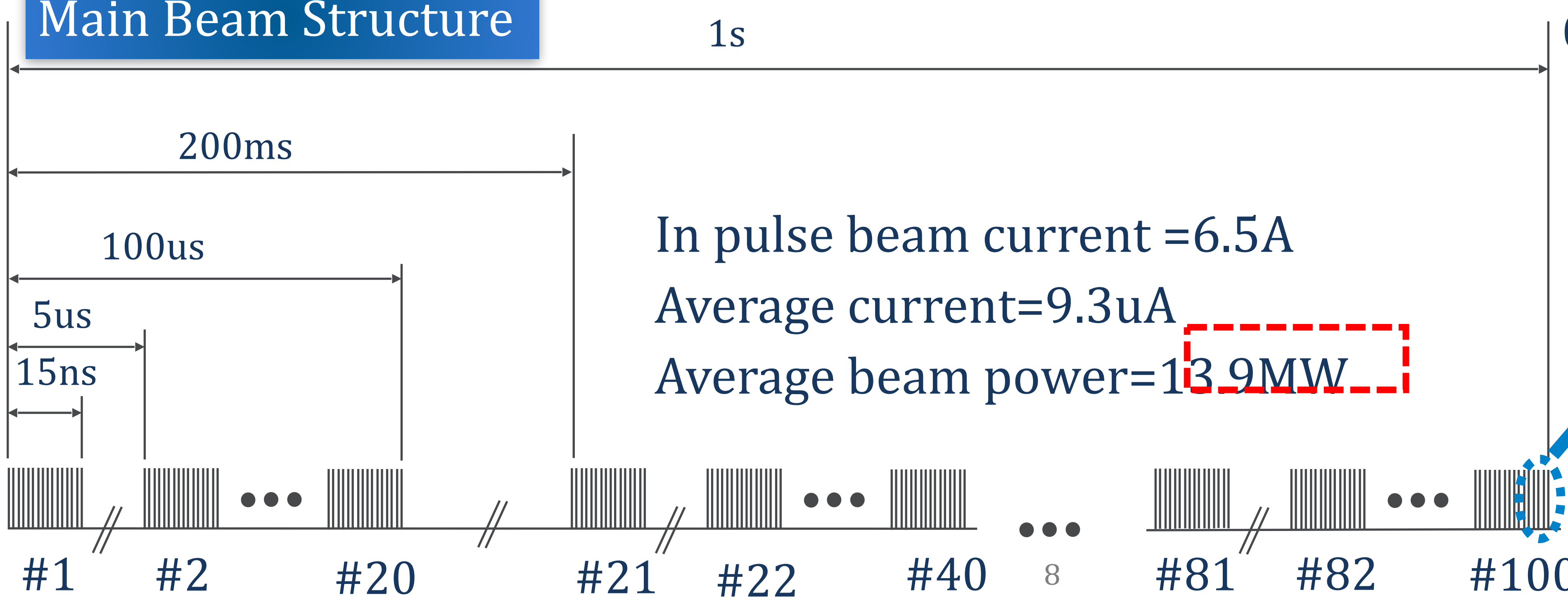
Demanding requirements but within reach of what is already in development for XFELs, EIC etc

SWFA TWO-BEAM ACCELERATOR LINEAR COLLIDER

3TeV 30MW beam power TBA



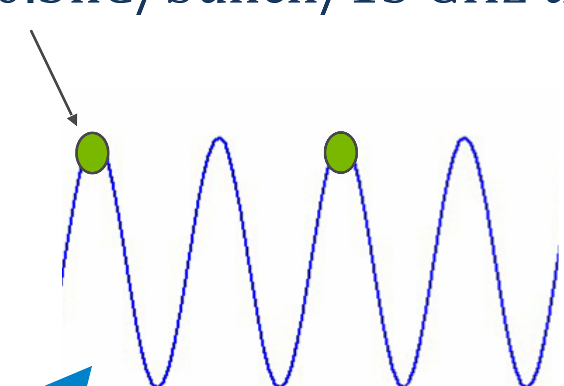
Main Beam Structure



In pulse beam current =6.5A

Average current=9.3uA

Average beam power=13.9MW

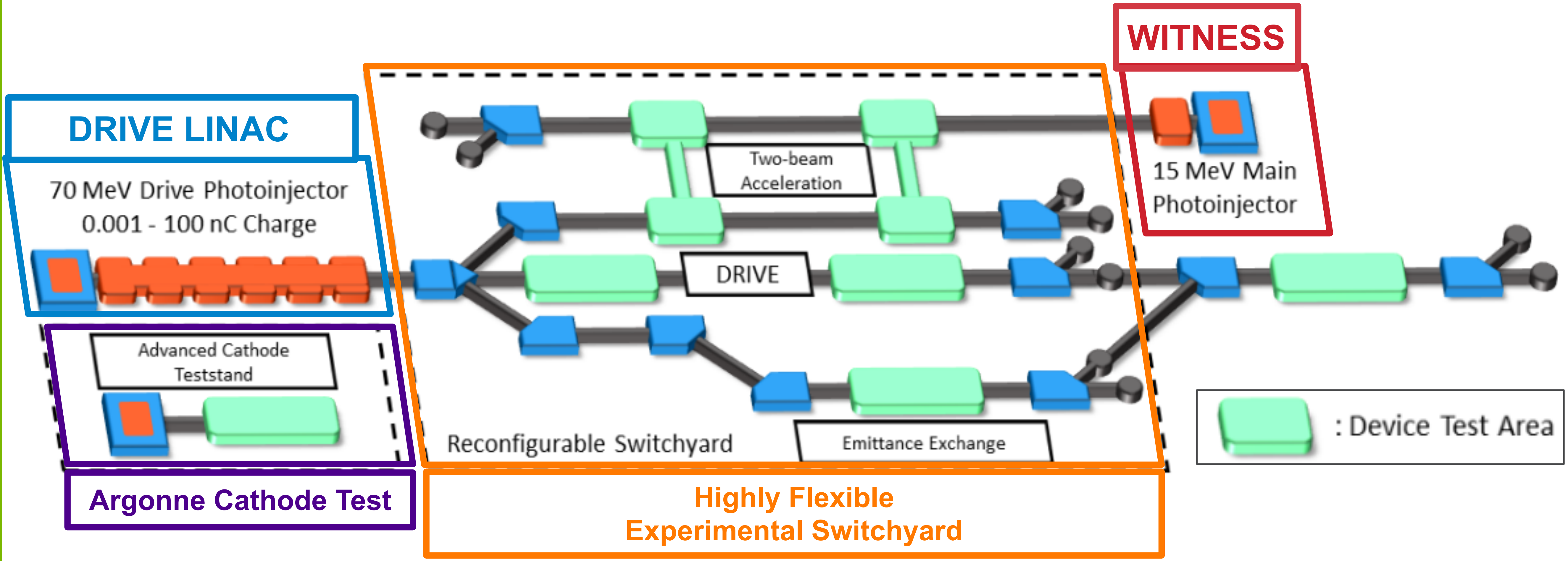


Main Bunch Shaping need for efficiency

Courtesy of John Power

THE ARGONNE WAKEFIELD ACCELERATOR FACILITY

GARD Test Facility capabilities enable beam-driven wakefield acceleration



Drive RF Photoinjector (65 MeV)

- 0.1-100nC bunches
- 600-nC bunch trains (40 J)

Witness RF photoinjector (15 MeV)

- Provides two-beam capability
- Bright beams for low-energy experiments

Argonne Cathode Test Stand (2-4 MeV)

- Cathode research and diagnostics
- Physics of high-gradient breakdown

Experimental Switchyard

- Highly reconfigurable
- 6D phase space manipulation

Courtesy of John Power

Development of High-Brightness Electron Sources

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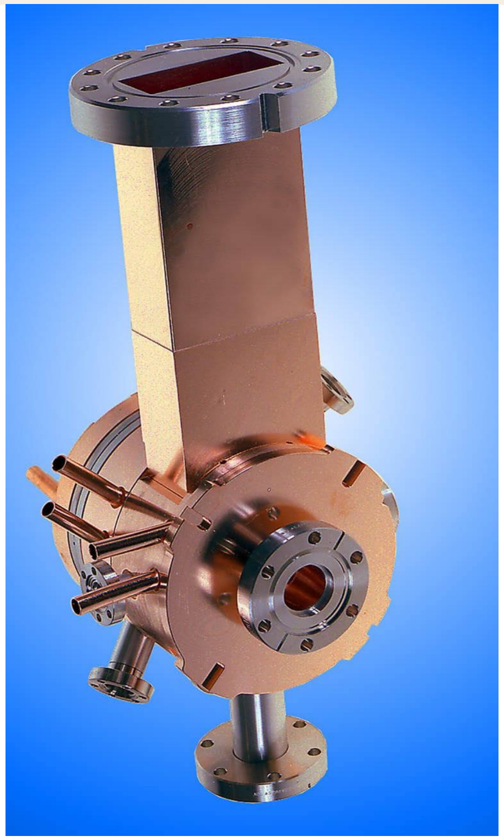
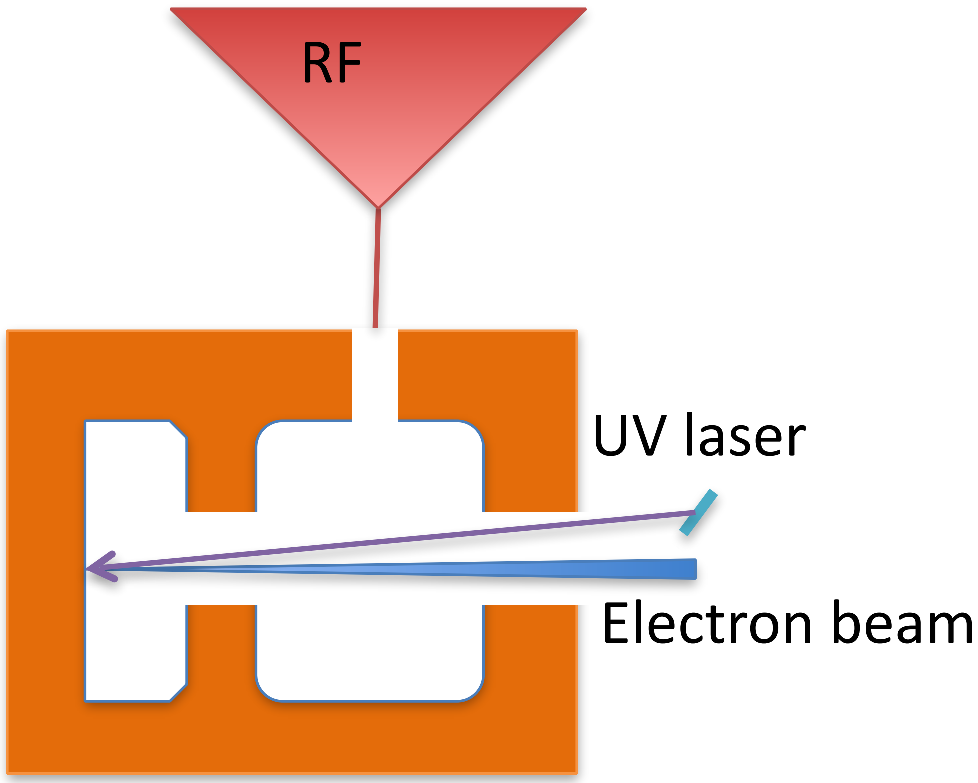
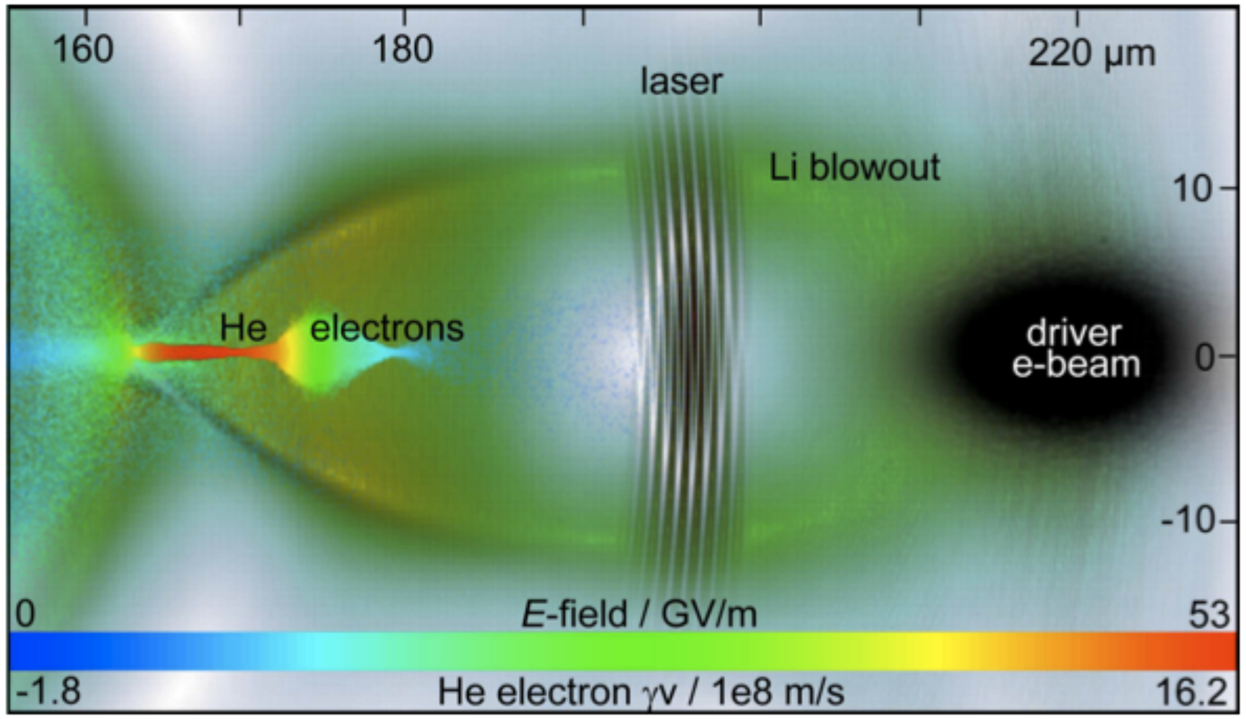
LCLS Style Photoinjector

- 100MeV/m field on cathode
- Laser triggered release
- ps beams, mm size - multi-stage compressions & acceleration
  - Tricky to maintain beam quality (CSR, microbunching…)







Plasma Photoinjectors

- 100 GeV/m
- fs beams, µm size
- Promise orders of magnitude improvement in emittance
- Injection from: TH, Ionization, DDR, CP…

Simulated Beam Brightness for Plasma Based Injectors

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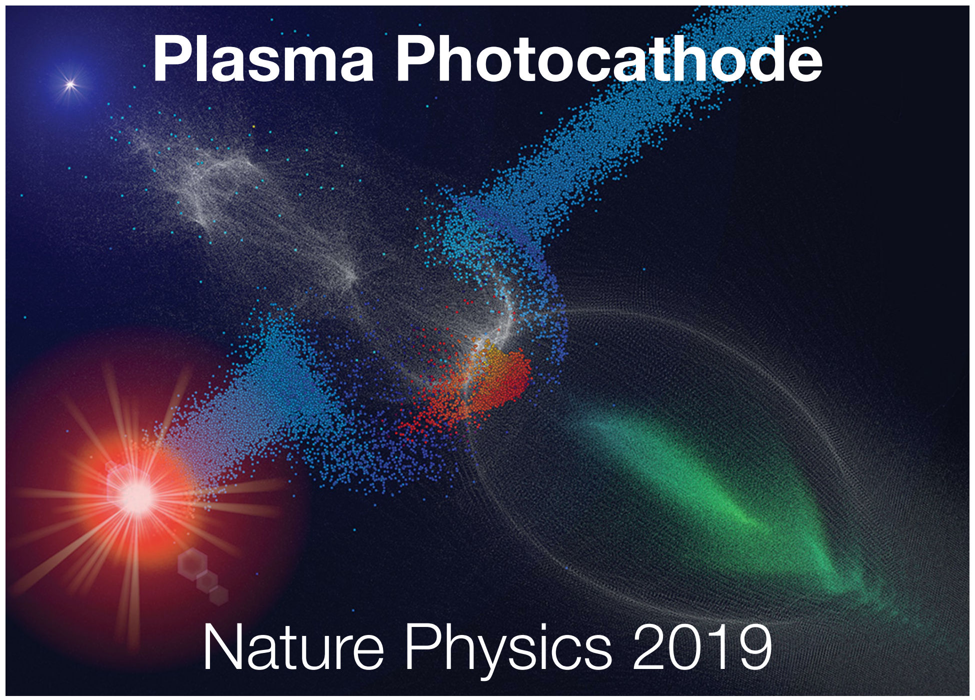
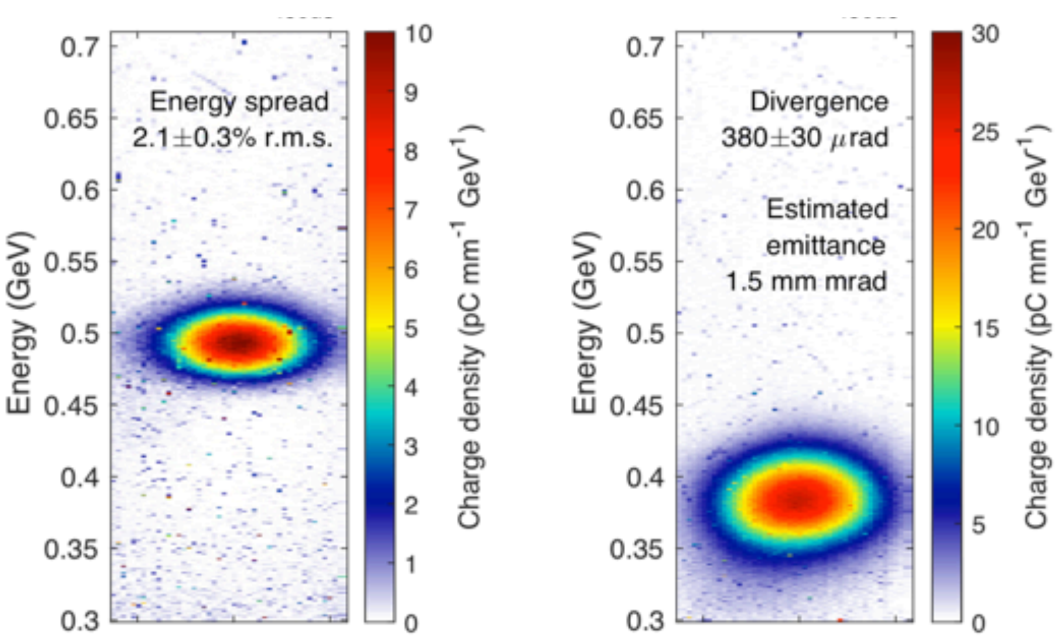
		I [kA]	ε_N [nm]	σ_E [MeV]	B [A/m²/rad²]
Ionization Injection[1]	Trojan Horse	~0.3	40	several	10^{18}
	Downramp-assisted Trajan Horse	~1	20	2.2	10^{19}
	Transverse colliding	~0.4	8.5/6	0.2, 0.012 (slice)	10^{19}
	Two-color: Longi.	~0.3	50	1~2	10^{17}
	Two-color: Trans.	~0.03	60	1, 0.03 (slice)	10^{16}
Downramp Injection[2]	Laser (10^{19} cm^{-3})	~10	10	0.3	10^{20}
	Beam (2.8e18 cm^{-3})	~10	30	0.5	10^{19}
	Beam (10^{20} cm^{-3})	~10	4	0.2	10^{21}
	Evolving Beam injection (10^{19} cm^{-3})	~10	10	0.5	10^{20}

[1]B. Hidding, et al., PRL 108, 035001 (2012); A. Knetsch, et al., arXiv:1412.4844v1; F. Li, et al., PRL 111, 015003 (2013); L. L. Yu, et al., PRL 112, 125001 (2014); X. Xu, et al., PRST-AB 17, 061301 (2014).
[2]FACET-II Proposal V6 (2013); X. Xu, et al., PRAB 20, 111303 (2017); T. Dalichaouch, et al., PRAB 23, 021304 (2020).

Development of High-Brightness Plasma Injectors: Experiments @ FACET-II



- FACET experiments demonstrated concepts
- Measured beam parameters inline with expected values from simulations
- Experiments at FACET-II will pursue and optimize several techniques for generating beams with unprecedented brightness



Demonstrated @ FACET	Proposed @ FACET-II
Normalized Emittance:	Normalized Emittance:
• 1.5 mm-mrad	• 0.01 mm-mrad
Bunch Charge & Duration:	Bunch Charge & Duration:
• 20pC & 100fs	• 20pC & 20fs
Energy & Energy Spread:	Energy & Energy Spread:
• 0.5 GeV with 2%	• > 1 GeV with 1%

Beam Brightness scales with plasma density. Short FACET-II Bunches are a competitive advantage over other facilities.

FACET-II Layout and Beams

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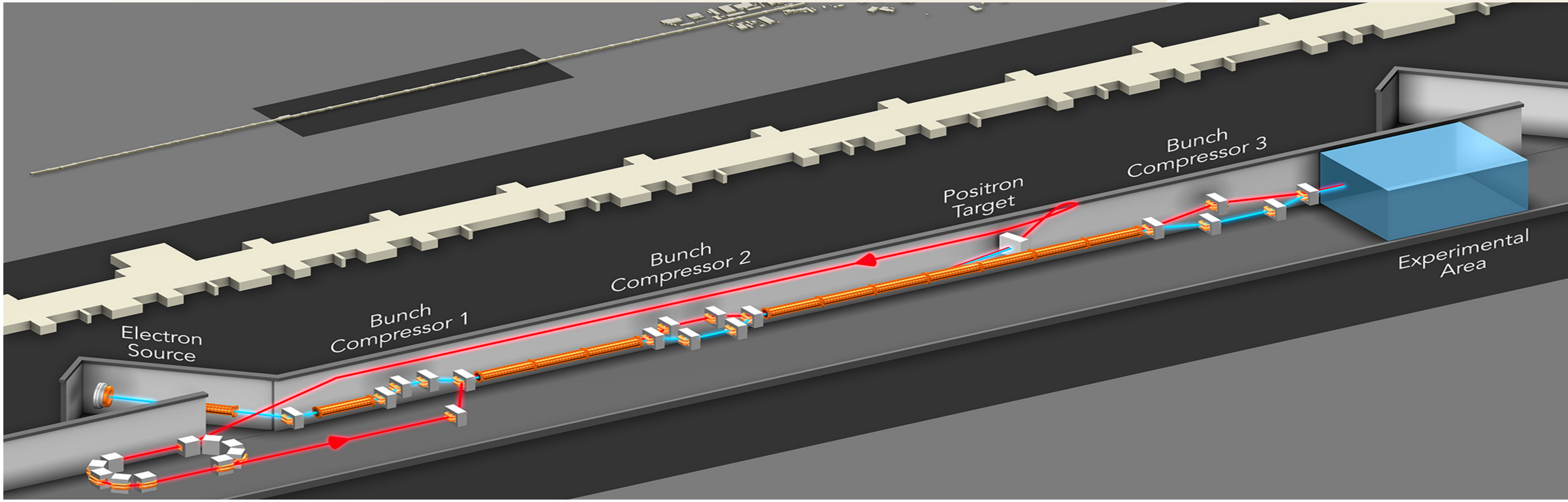
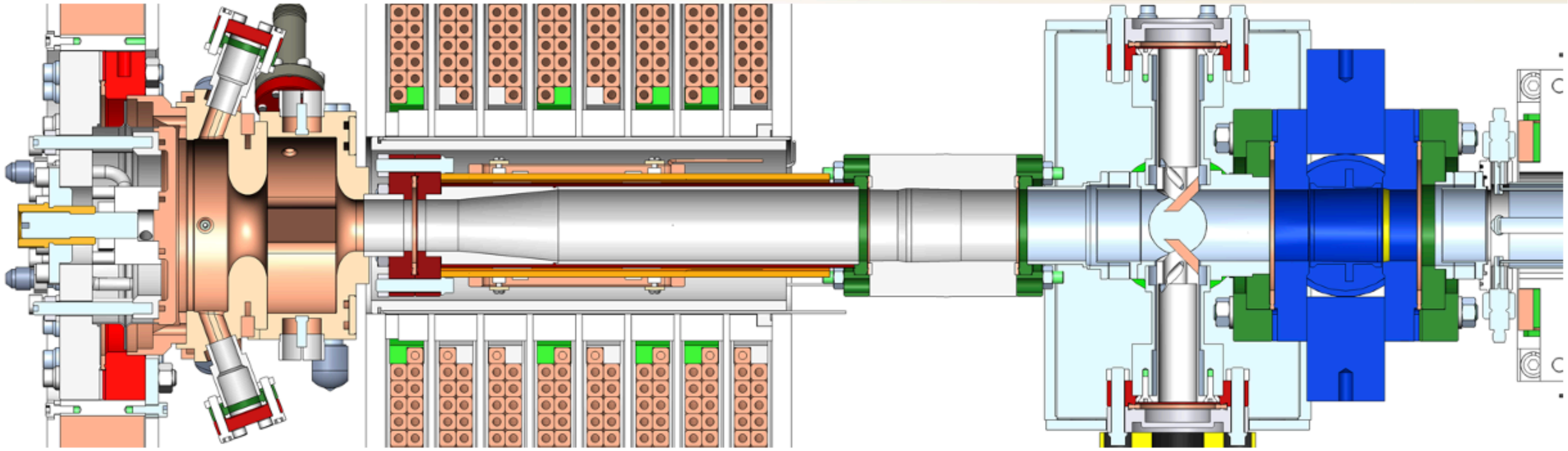
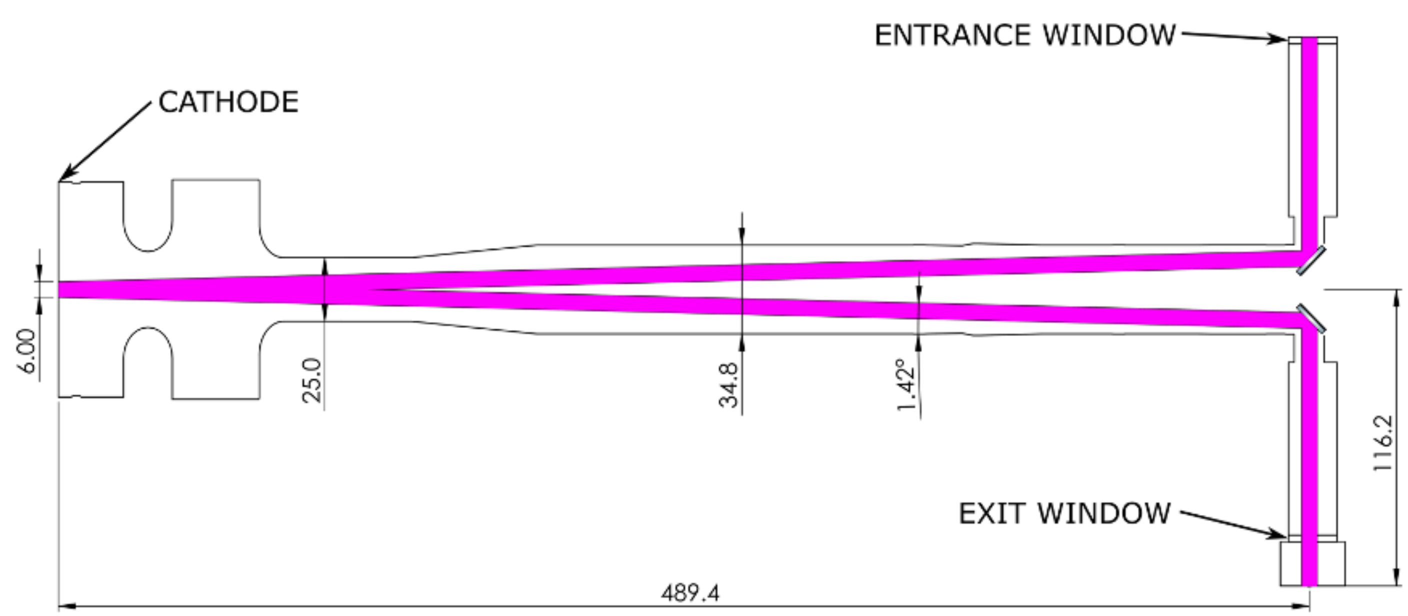


Electron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	2	0.7-5
Repetition Rate [Hz]	30	1-30
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]	4.4, 3.2	3-6
Spot Size at IP $\sigma_{x,y}$ [μm]	18, 12	5-20
Min. Bunch Length σ_z (rms) [μm]	1.8	0.7-20
Max. Peak current I_{pk} [kA]	72	10-200

Positron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	1	0.7-2
Repetition Rate [Hz]	5	1-5
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19	10, 10	6-20
Spot Size at IP $\sigma_{x,y}$ [μm]	16, 16	5-20
Min. Bunch Length σ_z (rms)	16	8
Max. Peak current I_{pk} [kA]	6	12

FACET-II Gun and Laser Input Geometry

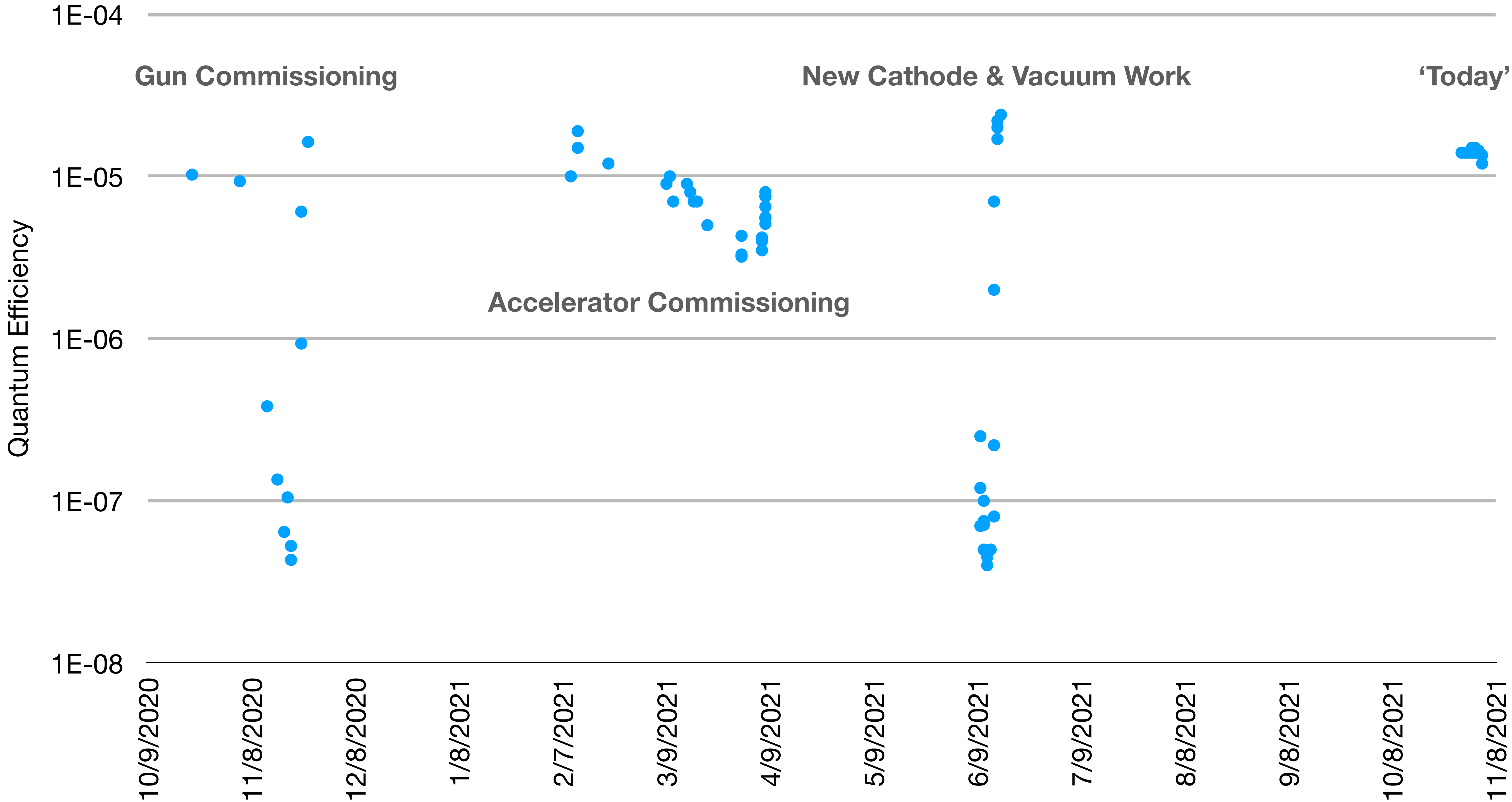




- LCLS style Photoinjector, Cu cathode, 266nm laser, 3.8ps FWHM, 5.5mm diameter, gun vacuum 1-2E-10
- Measure laser energy input to gun vacuum window, at cathode ~75% (T_w~90%, R_m~80%)
- Charge measured on Faraday cup and BPMs
- Measured at peak Schottky phase, design phase ~70% peak yield, 10MW, 5.5-6MeV

FACET-II Operation with 2nC/bunch Need QE > 4E-5
Recall: LCLS Designed for 1nC, Operates at 20-250pC

History of FACET-II gun cathode QE after laser cleaning



Gun Vacuum Similar to LCLS Gun
But QE Behavior Suggested Cathode Contamination

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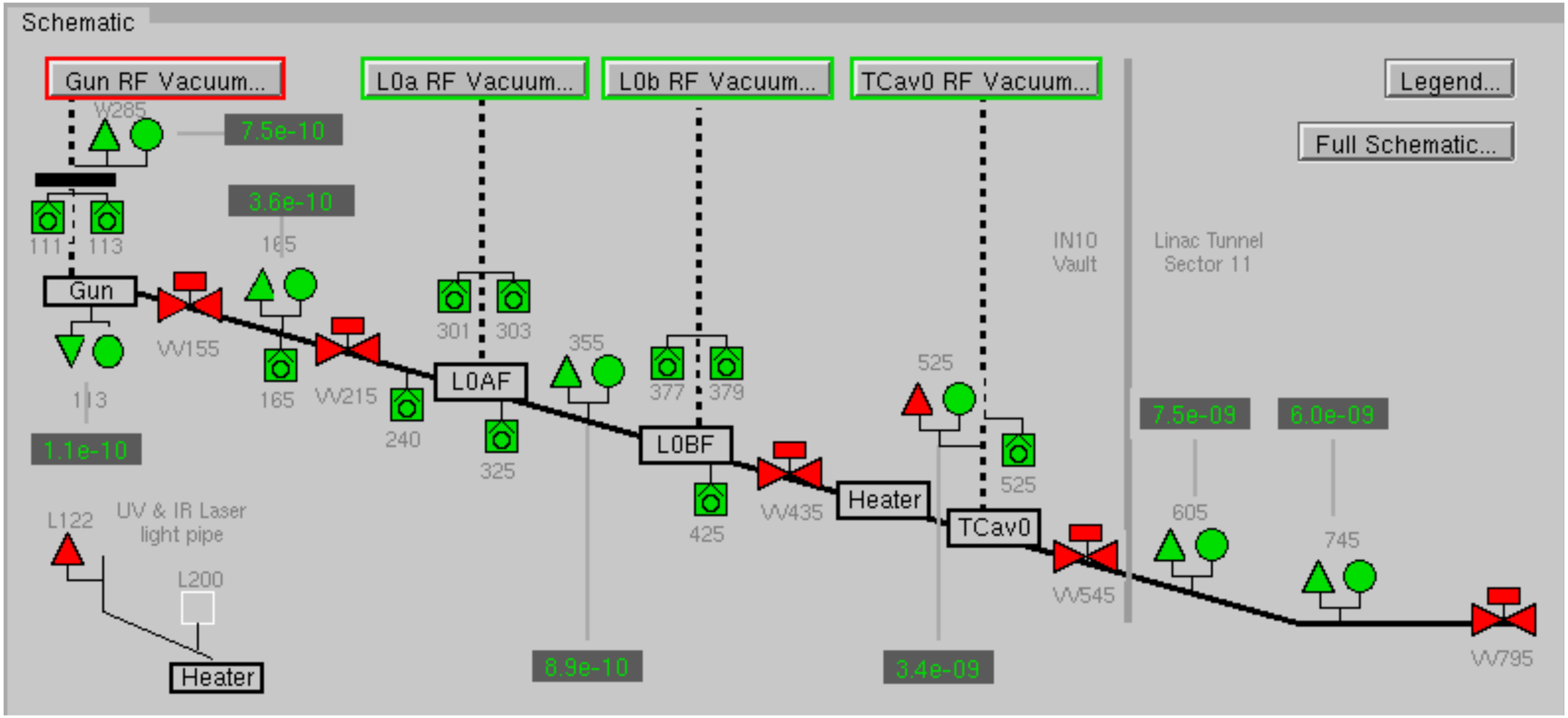
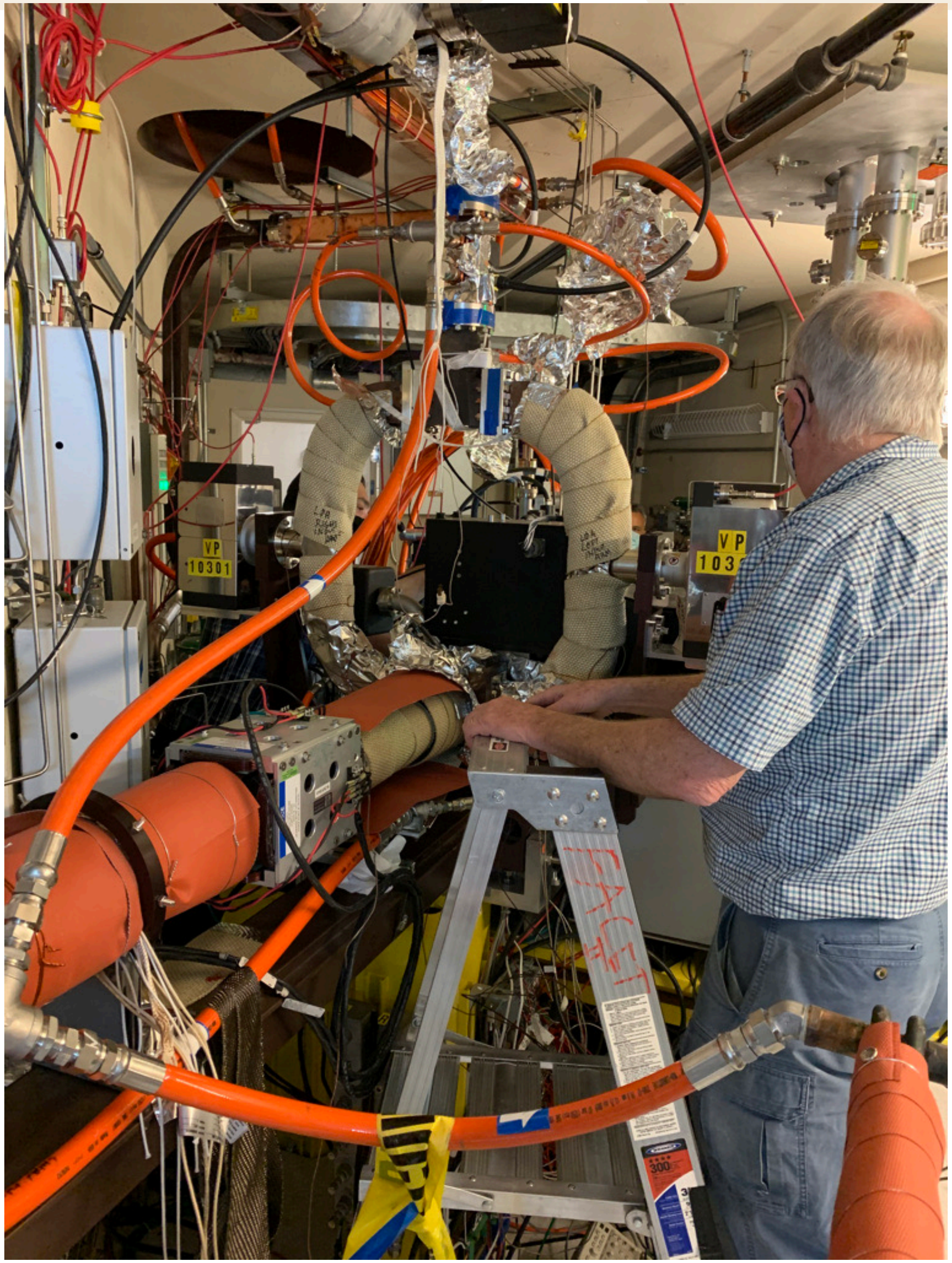


- During injector and accelerator commissioning, expect small vacuum leaks developed causing rapid (8 hour) QE degradation
- Large system, lots of pumping and small leaks were not obvious until shut off pumps and looked at rate of rise in isolated sections

Looks Easy in PowerPoint but Many Long Waveguide Runs
Some example areas: VP415 & L0A Input Coupler

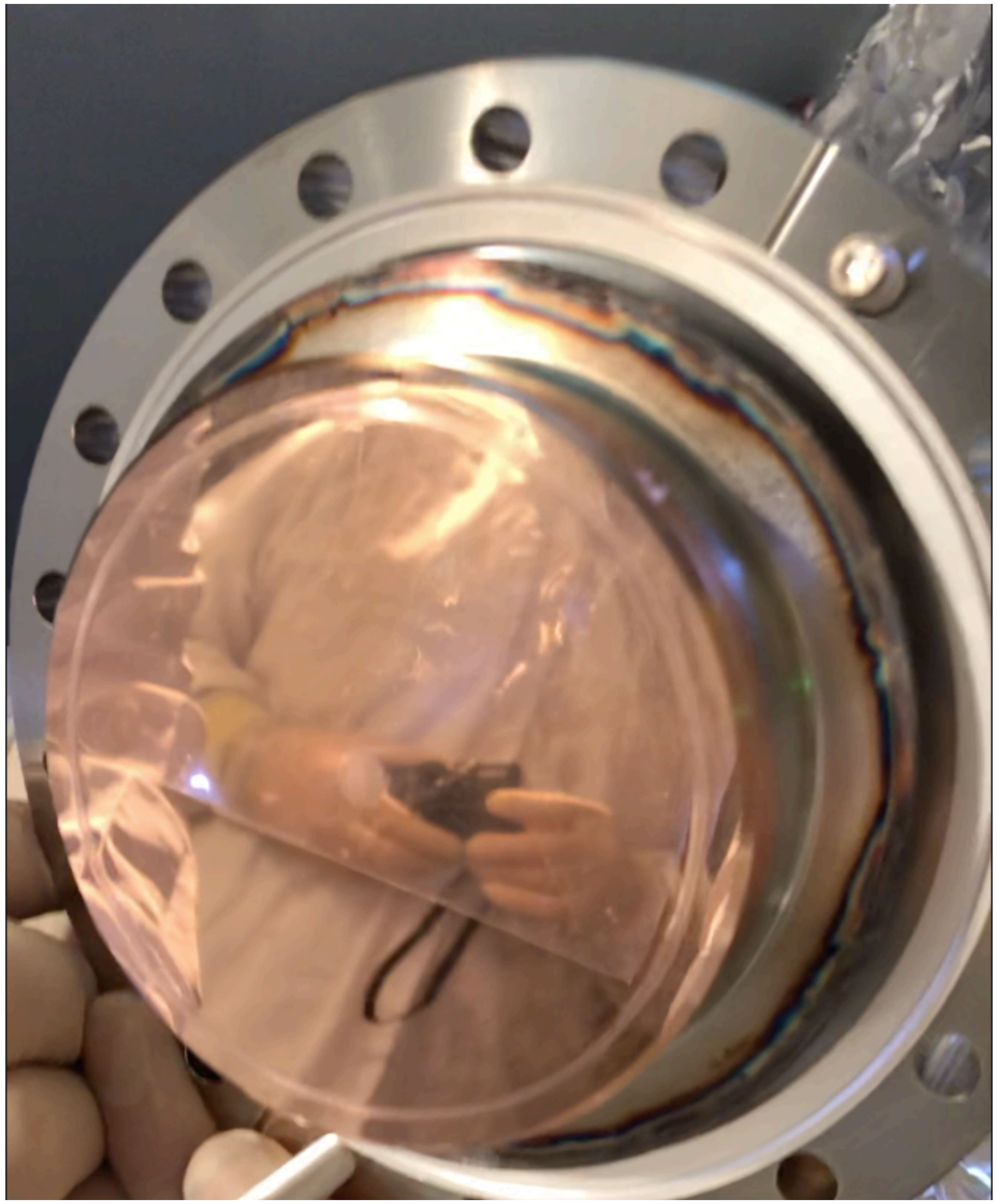


After Extensive Leak Checking and Mitigations FACET-II Cathode Changed Successfully April 28, 2021

LCLS cathode preparation steps.

Step 1: Cathode braze, dry H_2 at 1040 °C
~~Step 2: Vacuum fire at 650 °C for 24 h~~
Step 3: Rough machining
Step 4: Diamond fly cut
Step 5: Vacuum fire at 650 °C for 24 h
Step 6: Weld the cathode to flange
~~Step 7: Measure QE in the test chamber~~
~~Step 8: Plasma cleaning in the test chamber (option)~~
Step 9: Exposed to air (due to lack of load lock system) for the installation in the gun

F. Zhou et al. *Establishing reliable good initial quantum efficiency and in-situ laser cleaning for the copper cathodes in the RF gun*, NIM-A **783 (**2015)



One cathode in the current spare pool (S/N 148), the original cathode in the FACET-II gun (S/N 146), and the one in question (S/N 147) have all been processed through steps 1, 3, 4, 5, and 6. Three additional spare cathodes (S/Ns 119, 120, and 123) have been processed through 1, 4, 5, and 6 (no rough machining prior to diamond fly cutting). Of the spares, two are installed in CTCs (cathode test chambers) and two are in a vacuum bell jar. The first vacuum firing, step 2, is not done since step 5 accomplishes the same thing. None of the cathodes have been plasma cleaned and I don't think we measured the QE of any of the cathodes after the ASTA test program.

For 2nC/bunch Operation Need QE ~ 4E-5

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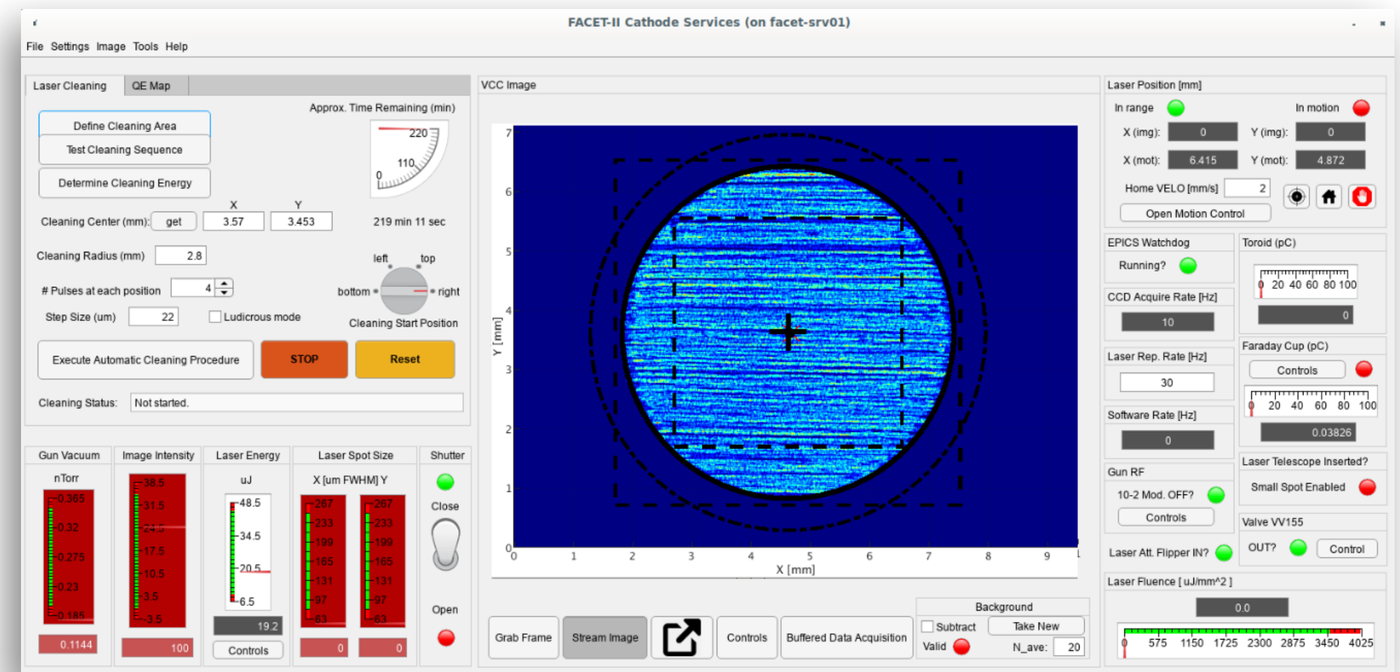
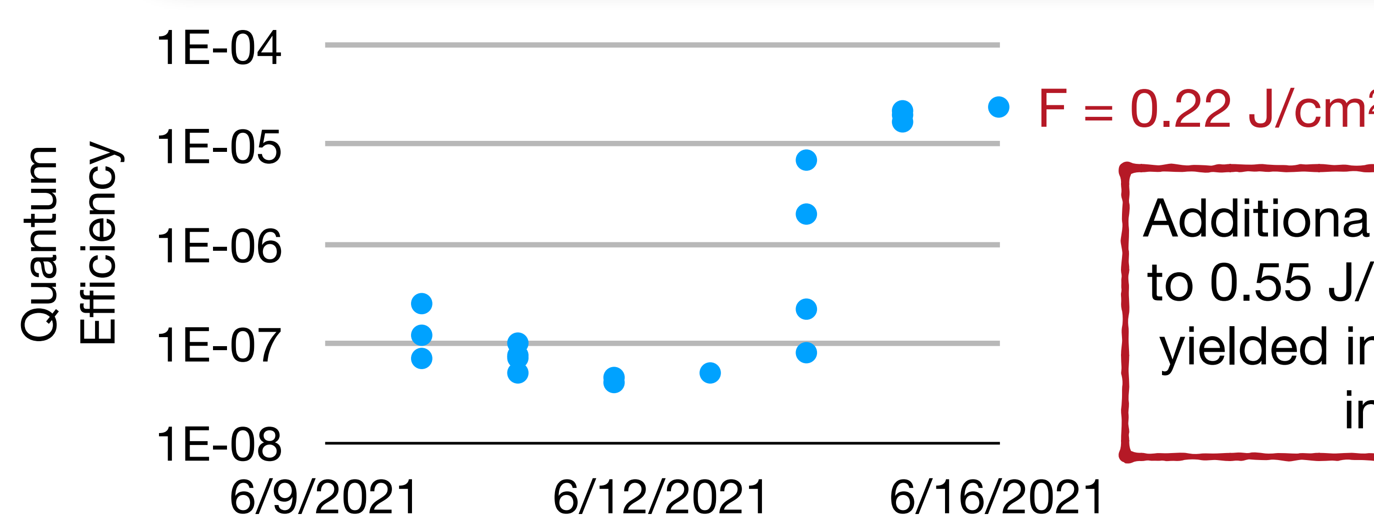
- Initial QE of new cathode too low for KPP and Operations
- Spoke to our colleagues at SLAC LCLS/ASTA, BNL ATF

Our recipe:

- Set initial fluence to produce minimum detectable vacuum rise (~2E-11)
- Raster over desired cathode area (5.5mm diameter), horizontal and vertical
- Measure dark current
- Measure QE
- Increase fluence ~10%
- Repeat
- Note - with 30Hz laser takes six hours per pass

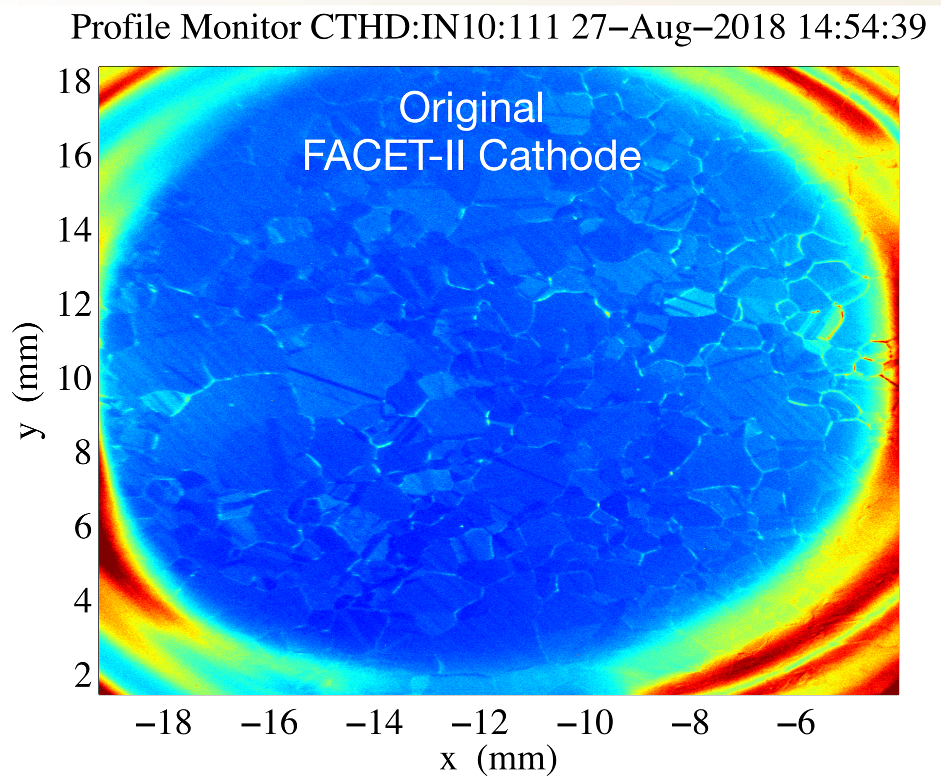


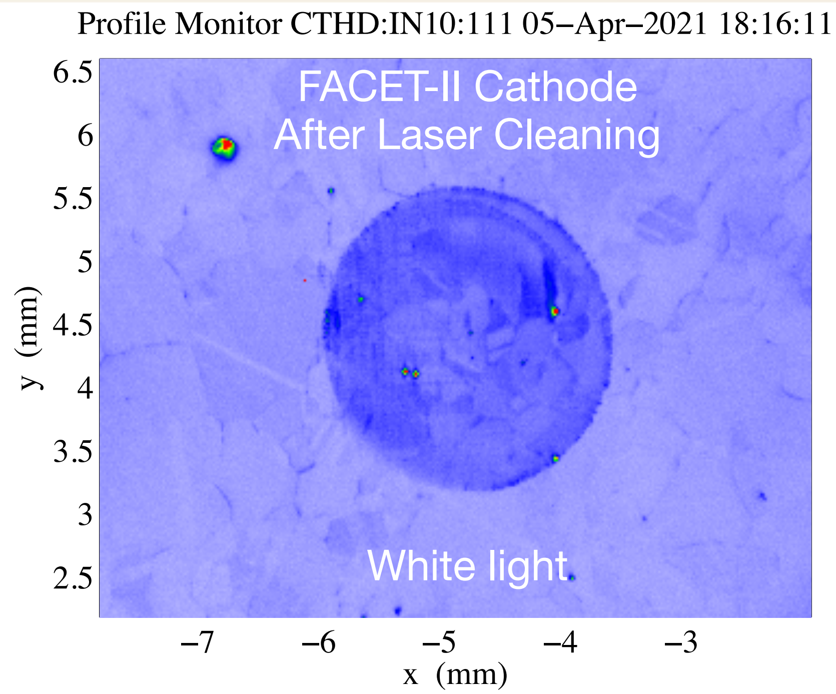


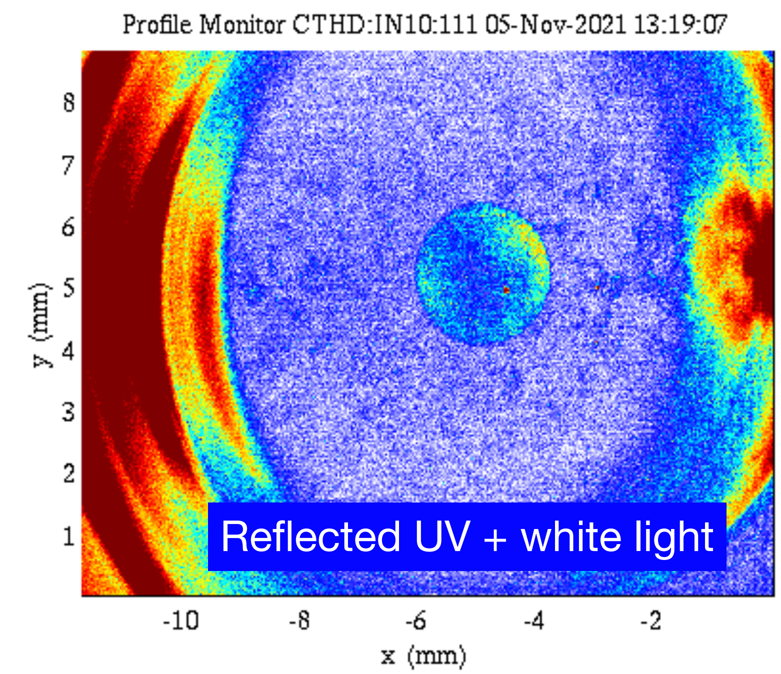
Additional cleaning up to 0.55 J/cm2 has not yielded improvement in QE

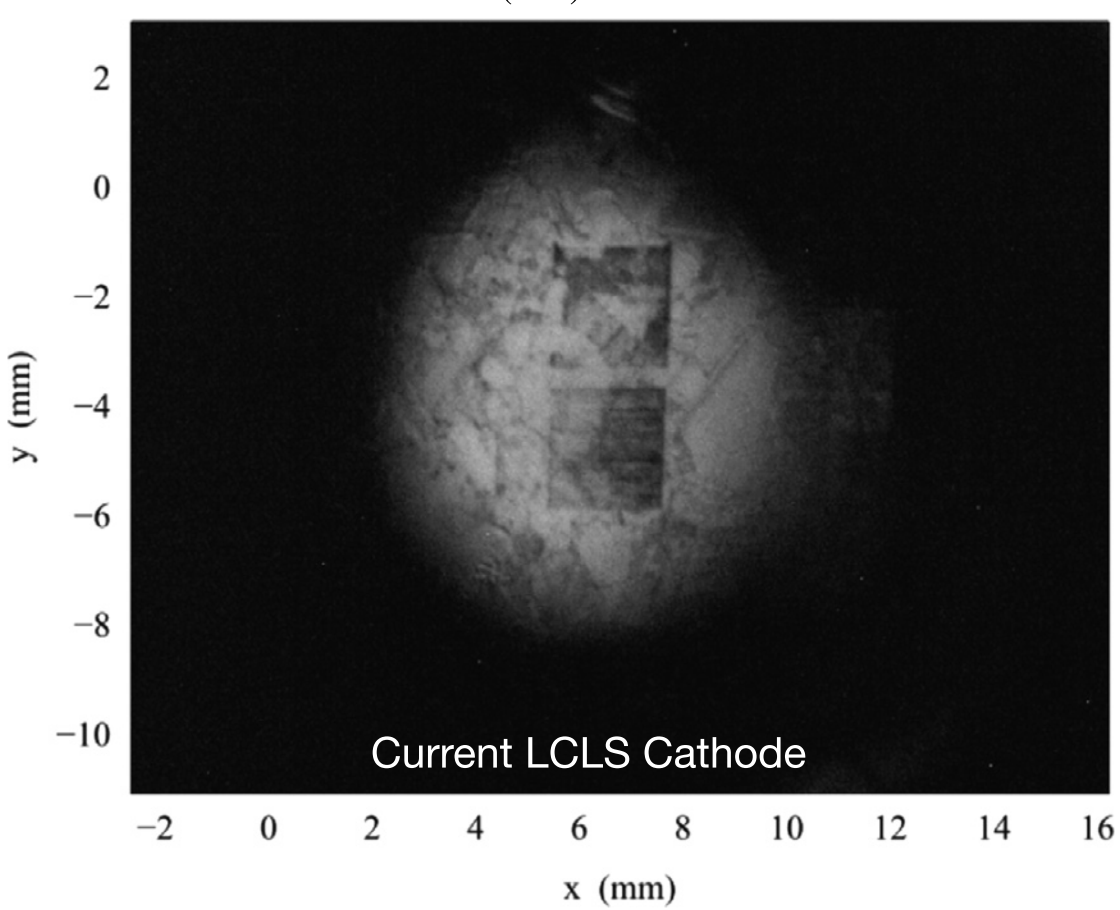
Laser cleaning is like baking, lots of recipes, some science and a lot done to taste

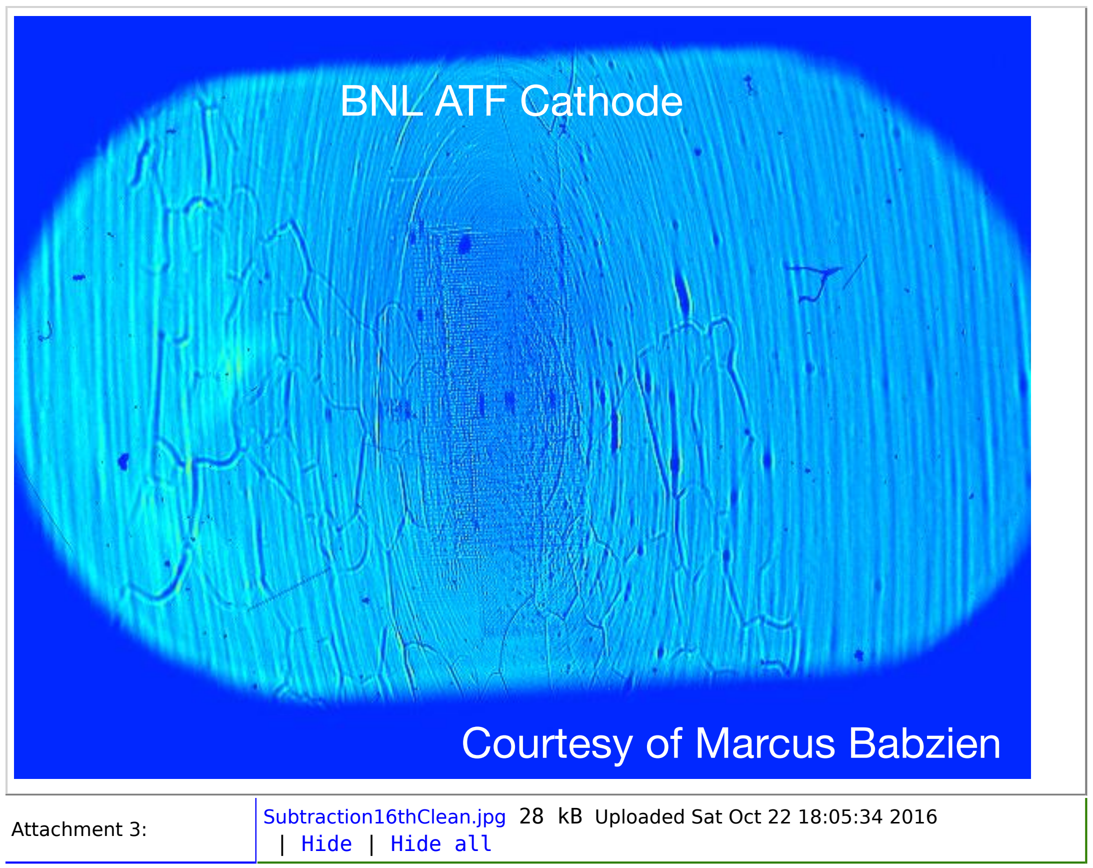
Laser Cleaning Modifies Cathode Surface











Next Steps: Laser Wavelength Matters
Switch FACET-II Laser from 266 to 253nm

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PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 074201 (2009)

Quantum efficiency and thermal emittance of metal photocathodes

David H. Dowell and John F. Schmerge
SLAC, Menlo Park, California 94025, USA
(Received 2 May 2009; published 27 July 2009)

It is noted that analytical expressions relating QE to work function ϕ_w and intrinsic emittance ε_x can be given by the following equations [8]:

$$QE(\lambda) = \frac{1-R(\lambda)}{1+\frac{\lambda_{opt}(\lambda)}{\lambda_{e-e}(\lambda)}} \frac{\left(h\nu-\phi_{eff}\right)^2}{8\phi_{eff}\left(E_F+\phi_{eff}\right)} \quad (1)$$

$$\frac{\varepsilon_n}{\sigma_x} = \sqrt{\frac{h\nu-\phi_{eff}}{3mc^2}} \quad (2)$$

with $\phi_{eff} = \phi_w - 0.037947\sqrt{E_0}$, where $QE(\lambda)$ is the QE dependence on the laser wavelength; λ is the laser wavelength, R is the cathode optical reflectivity, 0.43 for a copper at 253 nm, $h\nu$ is the photon energy, about 4.91 eV for 253 nm of wavelength, λ_{opt} is the photon absorption length of 116 Å, λ_{e-e} is electron–electron mean-free path about 22 Å, E_f is the Fermi energy, about 7 eV, ϕ_{eff} is the effective work function, mc^2 is the rest mass energy of electron, E_0 is the applied RF electric field on the cathode, expressed by $E_{peak}\sin(\varphi)$ in units of MV/m, E_{peak} is gun's peak accelerating gradient, 110 MV/m, and φ is the gun phase from zero-crossing,

Nuclear Instruments and Methods in Physics Research A 783 (2015) 51–57

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Establishing reliable good initial quantum efficiency and in-situ laser cleaning for the copper cathodes in the RF gun

CrossMark

F. Zhou *, J.C. Sheppard, T. Vecchione, E. Jongewaard, A. Brachmann, J. Corbett, S. Gilevich, S. Weathersby

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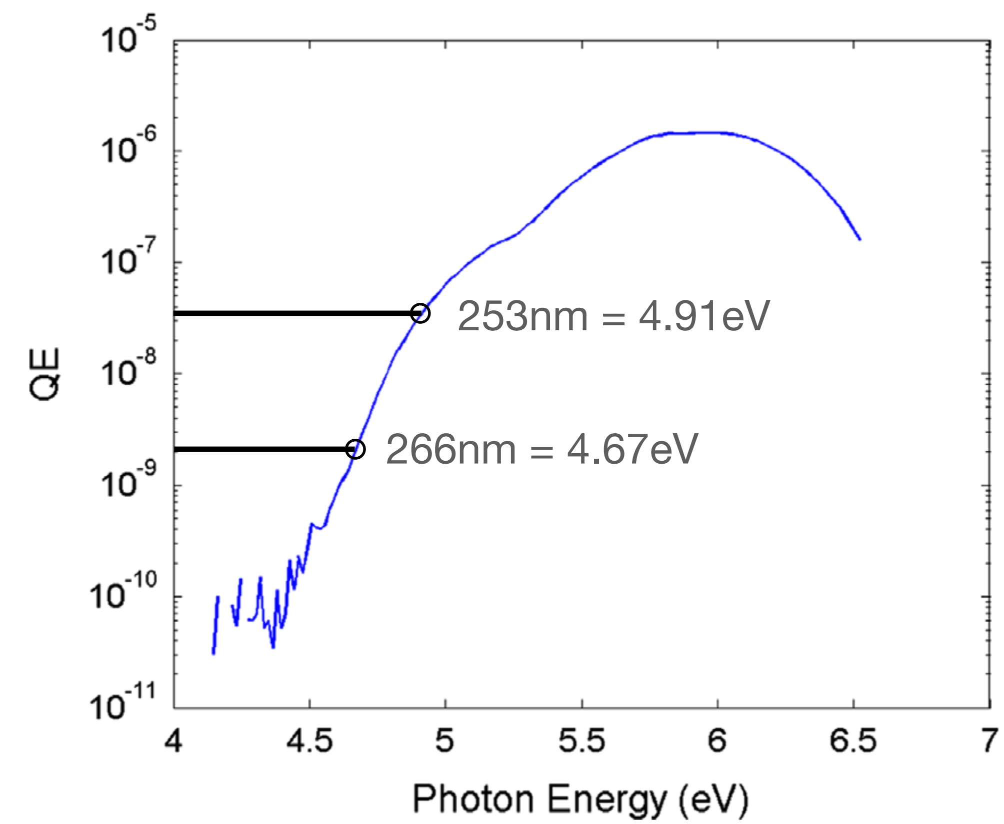

Fig. 3. Typical QE measured in the test chamber prior to installation in the gun. QE is $< 1 \times 10^{-7}$ at the photon energy of 4.91 eV (253 nm).

Looking for factor of three or more improvement with shift to shorter wavelength

Still New Approaches Being Developed for Cu Cathodes

SLAC

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Multiphoton Photoemission from a Copper Cathode Illuminated by Ultrashort Laser Pulses in an rf Photoinjector

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Enhanced QE possible:

- Multi-photon emission
- Short UV pulses

Intriguing SPARC_lab studies

- Blue (400nm)
- Larger energy available
- Better laser uniformity
- Less toxic for optics

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Optics Letters

Time-resolved study of nonlinear photoemission in radio-frequency photoinjectors

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Wavelength	Pulse Length	Pulse Energy	Expected Charge	Thermal Emittance
266nm	4ps	800μJ	2nC	2.2μm
266nm	400fs	500μJ	2nC	3.4μm
400nm	4ps	5mJ	2.1nC	2.8μm
400nm	400fs	1.5mJ	2.0nC	2.9μm

Preliminary studies for FACET-II
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Concluding Thoughts

- Advanced accelerator concepts are being investigated as candidates for a future generation of linear colliders
- Plasma and structure wakefield accelerators expect to benefit from decades of linear collider and XFEL R&D to produce the required high-charge high-repetition rate beam drivers
- Injectors based on plasma accelerators may serve as brightness transformers and allow novel intermediate applications such as light sources with higher photon energy, higher peak power or shorter pulses
- Current generation test facilities rely on 'proven' technology and are risk adverse with operating machines or new projects
- Flexible test stands and facilities, with sustained (not reactionary) R&D are critical to support current and next generation facilities

FACET-II Facility for Advanced Accelerator Experimental Tests

Questions?

11-NOV–2021

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