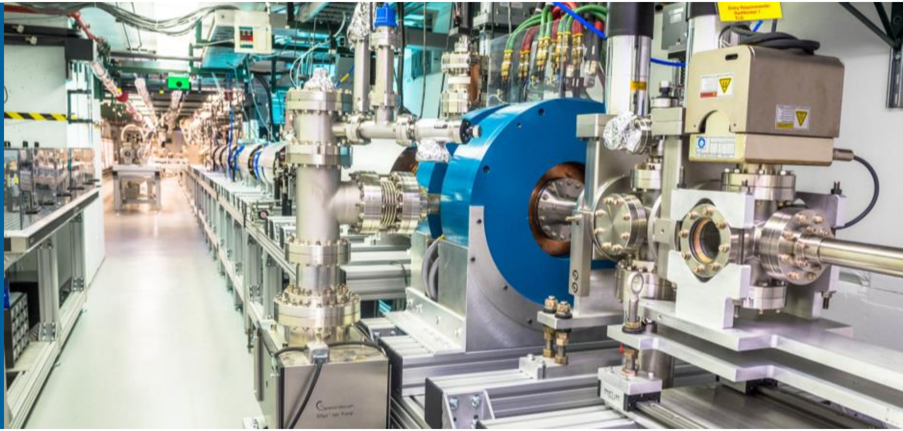
EXPERIENCE WITH HIGH CHARGE PHOTOINJECTOR OPERATION AT THE ARGONNE WAKEFIELD ACCELERATOR FACILITY.



JOHN POWER
Argonne Wakefield Accelerator, Argonne National Laboratory

July, 21, 2020
Joint DESY and University of Hamburg Accelerator Physics Seminar

ARGONNE WAKEFIELD ACCELERATOR (AWA)

The AWA's mission: R&D for future accelerators

- 5 accelerators at Argonne
- 30 minutes west of Chicago.
- Visitors Welcome!!

OUTLINE

- Introduction to AWA
  - Group & facility
  - Science
  - Beam parameters
  - Experiments
- AWA experience with high charge photoinjectors
  - Focus on practical lessons learned at AWA (80%)
  - Leave simulation work to PETRA-IV (20%)
- Summary/discussion

WHO WE ARE

THE AWA GROUP

THE AWA GROUP

Beam Physics

Philippe Piot
NIU/APS/AWA

(A) Group Leader

John Power

Advanced Accelerator Concepts

Chunguang Jing
Euclid/AWA

retired

Manoel Conde

Wei Gai

Controls & RF Systems

Wanming Liu

Mech. & Civil Engineering

Scott Doran

Beam Physics

Gwanghui Ha

Electron Sources

Eric Wisniewski

Advanced Accelerator Concepts

Xueying Lu
NIU/APS/AWA

Advanced Accelerator Concepts

Jiahang Shao

Making things work

Charles Whiteford

THE AWA STUDENTS

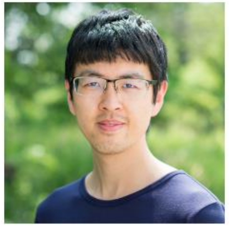
**All of these AWA students reside at Argonne.*

**AWA students are often PI's on the AWA's core R&D*

IIT | Tsinghua | IIT | Tsinghua

Nicole Neveu

2018



Lianmin Zheng

2018

Gongxiaohui Chen

current

Maomao Peng

current

UCLA | UW | NIU | UNIST | UPR | MSU

Ryan Roussel

2019

Jens Carter

summer

Tianzhe Xu

current

Jimin Seok

current

Tamara Gonzalez Acevedo

summer

Mitchell Schneider

current

ARGONNE COMMUNITY

Scientific collaboration inside ANL (multipurpose lab)

- **Argonne Accelerator Institute** (John Byrd)

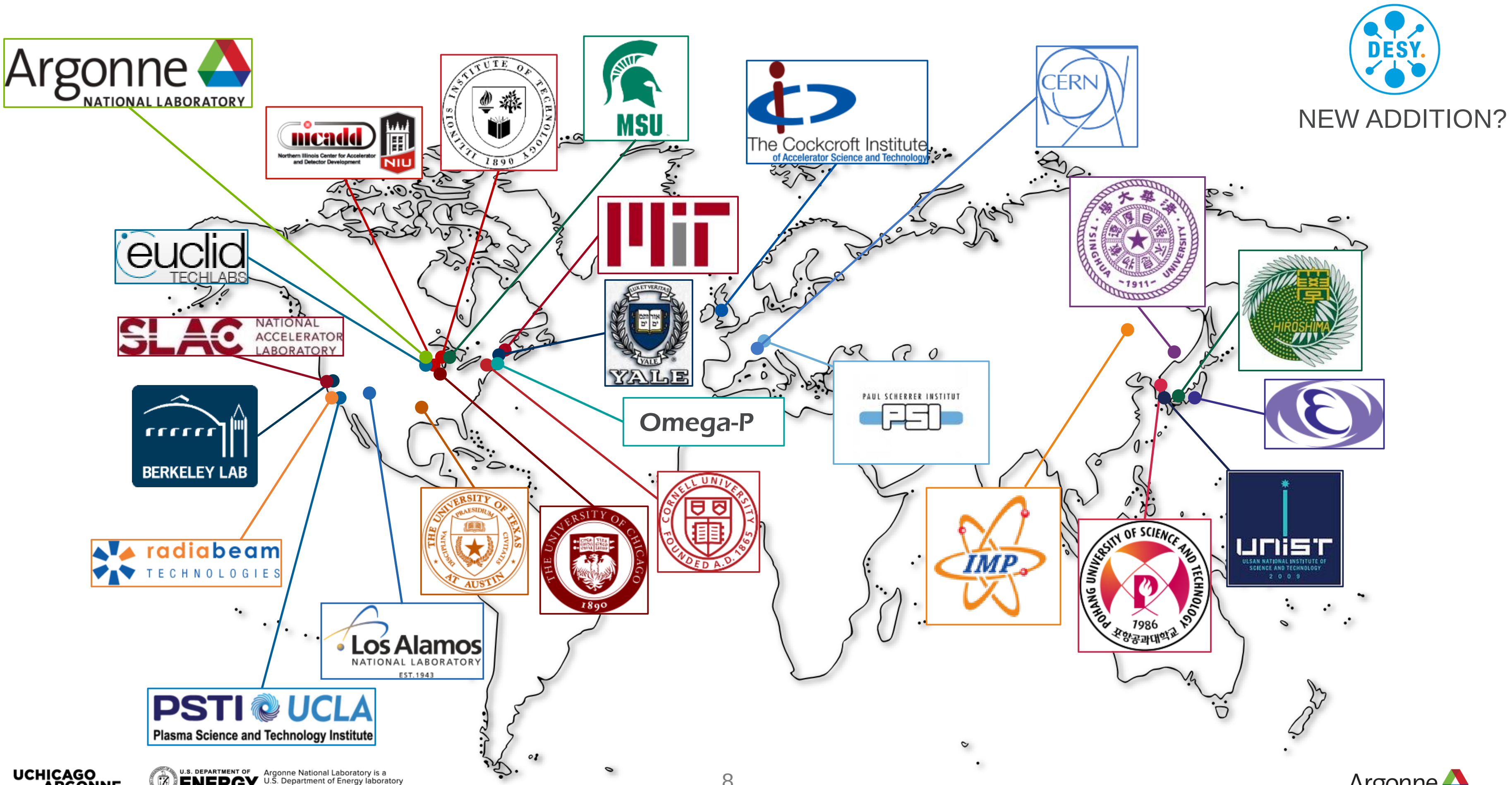
1. **APS** (Advanced Photon Source): https://www.aps.anl.gov/
2. **ATLAS** (Argonne Tandem Linac Accelerator System) in PHYS: https://www.anl.gov/atlas
3. **AWA** (Argonne Wakefield Accelerator) in HEP: https://www.anl.gov/awa
4. **LEAF** (Low Energy Accelerator Facility) in Nuclear Engineering: https://www.ne.anl.gov/facilities/leaf/
5. **EXM** (Electron and X-ray Microscopy) in CNM: https://www.anl.gov/cnm/electron-and-xray-microscopy

- **Math & Computer Science:** efficient optimization, machine learning, …
- **"User" Applications:** MSD (beam irradiation of samples), APS (radiation for medical therapy studies)

Technical expertise inside ANL (multipurpose lab)

- **HEP:** Electronics Group, Mechanical Group, Safety
- **ANL Central Shops:** machining, brazing, welding, metrology
- **APS:** Vacuum Shop (UHV cleaning), Ju Wang (high-voltage test of beam kicker, and bipolar supplies), Alex Cours (klystron modulator circuits), Jeff Dooling (laser diagnostics),
- **PHY:** (radiation shielding calculations for AWA bunker);
- **Other ANL divisions:** CNM (Ultrananocrystalline Diamond for cathodes); ES and CSE: (atomic layer deposition (ALD) to prevent multipacting); ES (tribology and metrology for ILC positron source) CNM (SEM for surface inspection)

AWA COLLABORATORS AND CONTRIBUTORS



WHO WE ARE

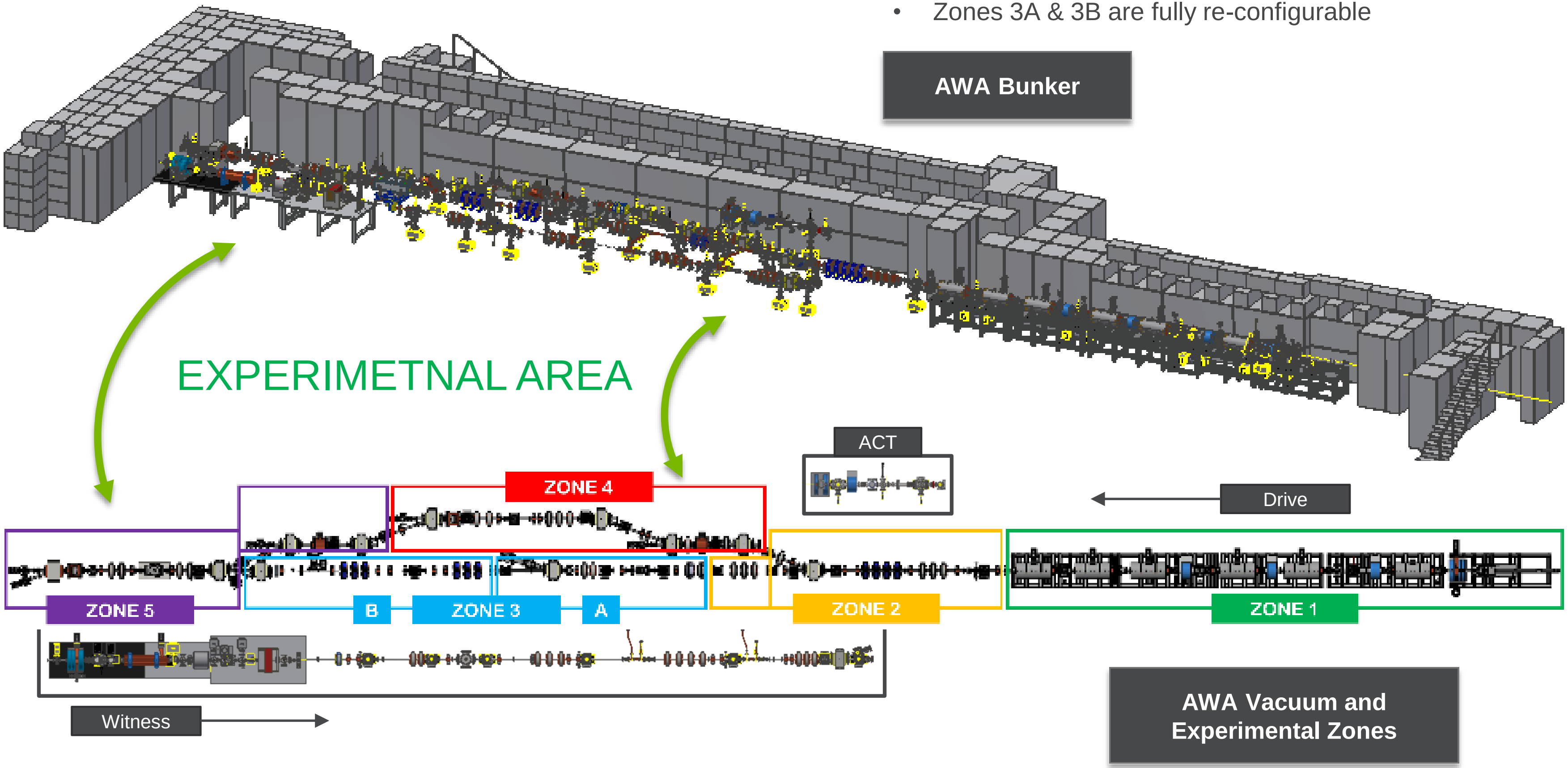
AWA FACILITY

- BEAMS
- EXPERIMENTAL AREAS

AWA FACILITY

Highly reconfigurable beamlines

- Zones 2-5 are experimental areas
- Zones 2, 4, and 5 have ~ 1 m experimental area
- Zones 3A & 3B are fully re-configurable



AWA FACILITY

Experimental Areas

(green)	Advanced Accelerator Concepts
(blue)	Accelerator and Beam Physics
(red)	Particle Sources

GUN TEST STAND

Upgrade to 1.5 cell RF gun with load-lock

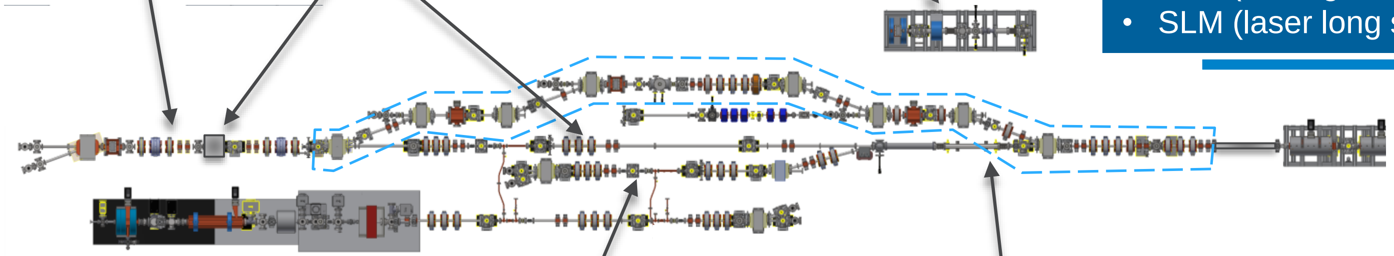
INJECTING MANIPULATED LASER

- α-BBO pulse stacker
- multi-splitter (train)
- MLA (homogenizer)
- SLM (laser long shaping)

GUN

Single-shot longitudinal phase space diagnostics

SWFA/PWFA test areas



65 MeV drive linac

15 MeV witness linac

Staging Beamline

6d emittance repartitioning

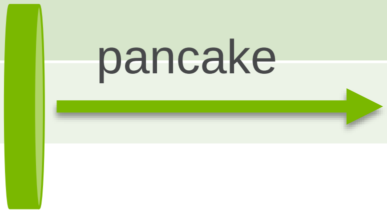
Double Emittance Exchange Beamline (longitudinal bunch shaping) + **Skew Quad Beamline (Round to Flat beam)**

AWA CAPABILITIES - BEAMS

Wide dynamic range

SINGLE BUNCH PARAMETERS

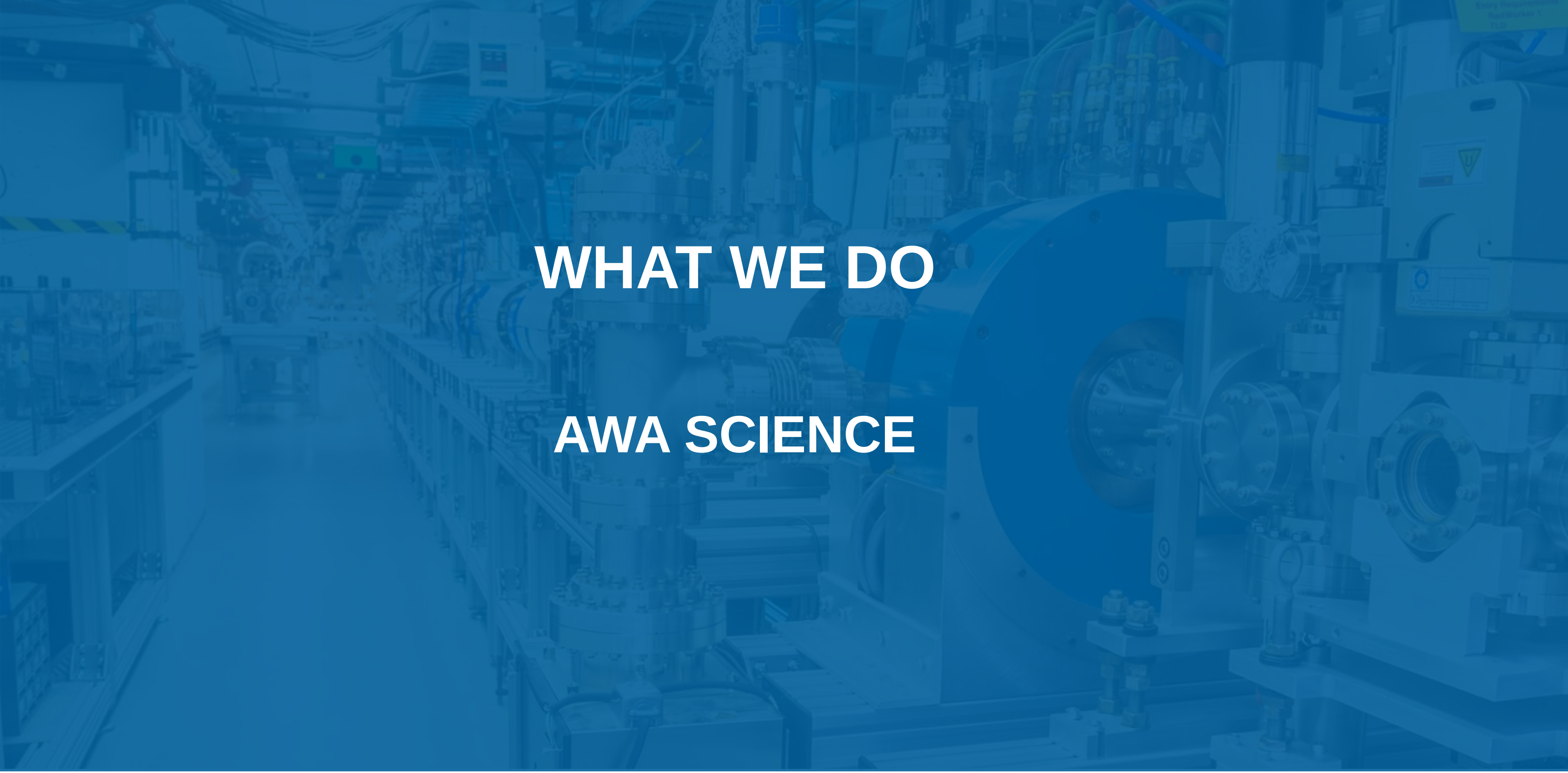
Beam parameters	Value	Note
Charge [nC]	0.1 – 100	*Have generated sub-pC beam but difficult to detect.
Energy [MeV]	6 – 63	
Rep. rate [Hz]	0.5 – 10	*2 Hz is nominal
Transverse laser diameter [mm]	0.5 - 22	*Uniform distribution (MLA)
Longitudinal laser pulse length [ps FWHM]	0.3	*Gaussian distribution **Flattop distribution (using α-BBO)
Bunch length [mm]	0.1 - 3	*High charge compression is not available
Transverse emittance [μm]	0.5 - 240	
Peak Current [kAmps]	0.5 - 25	



AWA CAPABILITIES - BEAMS

Variable Machine Configurations

Operation modes	Value		Methods
Bunch train	Modulation frequency [GHz]	**1.3 – 10^3**	1. Laser multi-splitter 2. Alpha-BBO 3. EEX+mask 4. EEX+transverse wiggler 5. TDC+mask (R&D)
	Charger per bunch [nC]	**<60**	
Longitudinal shaping	Shape	**Arbitrary**	1. EEX 2. TDC (R&D) 3. Laser based (R&D)
	Charge [nC]	**<5 → <20**	
Flat beam	Charge [nC]	**<5**	1. Angular momentum dominated beam + skew quads
	Emittance ratio	**<150**	
Transverse shaping	Available type	**1. Homogenization 2. Dot-array 3. Hollow**	1. MLA optics

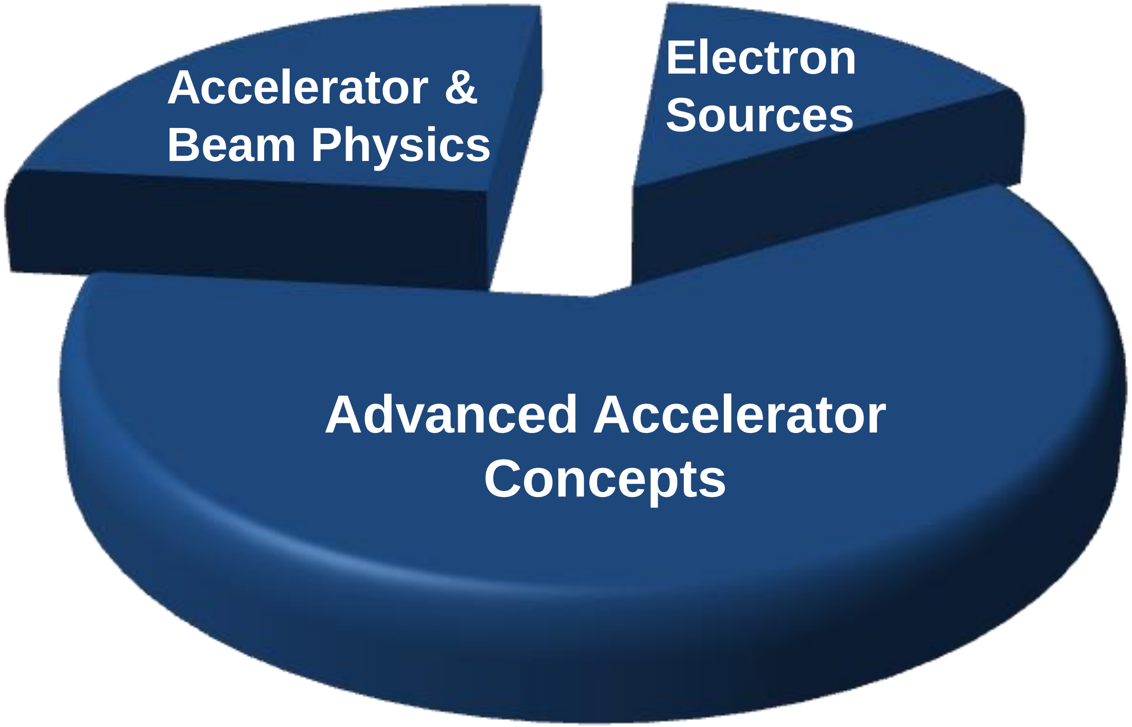


WHAT WE DO

AWA SCIENCE

AWA SCIENCE

~50/50 between in-house research & collaborators



AWA is not a user facility.

AWA & collaborators work together closely. (we don't merely provide beam.)

AWA MISSION

Developing the science and technology of electron beam generation, manipulation and acceleration for **electron beam-driven wakefield acceleration** and other applications.

Advanced Accelerator Concepts

- Wakefield acceleration
  - >300 MeV/m acceleration
  - 1 GV/m structure test
- High efficiency acceleration
  - Double rf-beam efficiency
- High power generation
  - 1 GW rf power extraction
- SWFA/PWFA ~90/10
- Breakdown studies

Accelerator and Beam Physics

- Large parameter space for tunable beamline
- 6D phase space manipulation. shaping, patterned beams.
- Instability suppression.
- Novel Diagnostics.

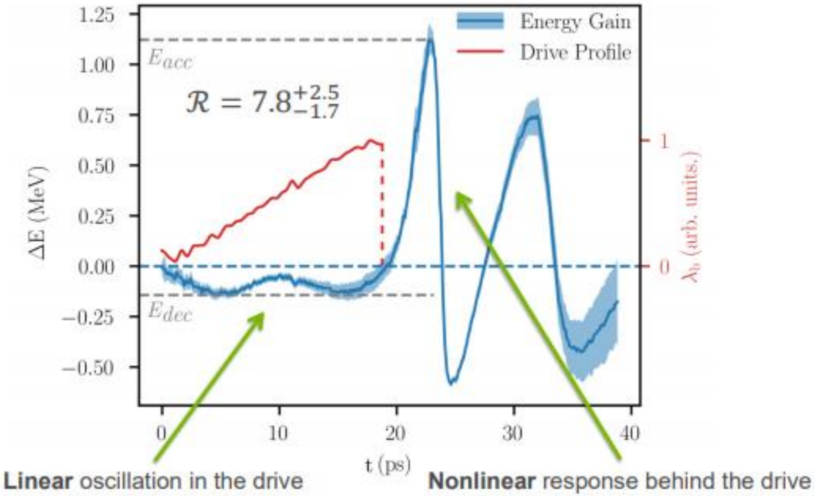
Electron Source

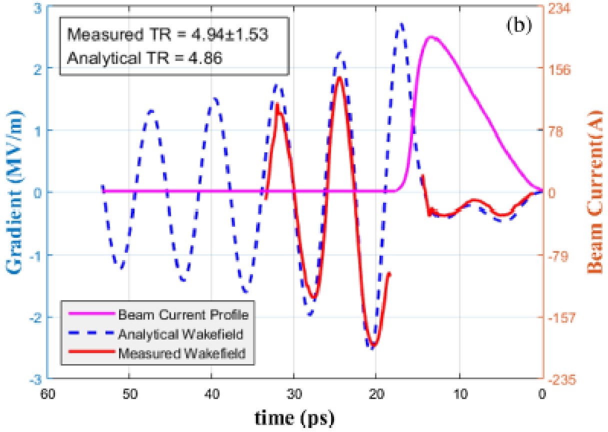
- High QE Cs_2Te cathode fabrication and operation
- FE cathode testing.
- Emittance correction (coupled-transverse-dynamicsaberration)

Stewardship

- UED/UEM
- Advanced cathode testing
- Collaboration work for future light sources
- Structure, beam physics, and source knowhow to medical/industrial applications

AWA – HIGH TRANSFORMER RATIO





$\mathcal{R} = 7.8^{+2.5}_{-1.7}$

PWFA Record

R. Roussel, et al, PRL 124, 044802 (2020)

$\mathcal{R} = 4.9 \pm 1.5$

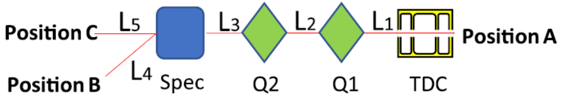
SWFA Record

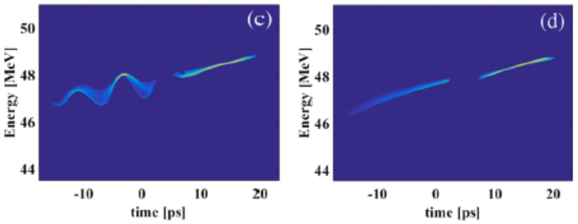
Q. Gao, et al, PRL 120, 114801 (2018)

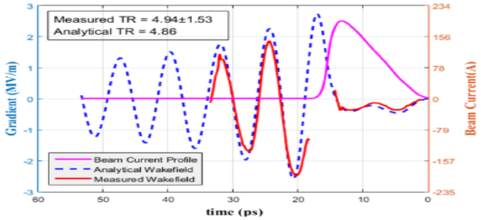
AWA DIAGNOSTICS

*G. Ha et al., in preparation (2019)

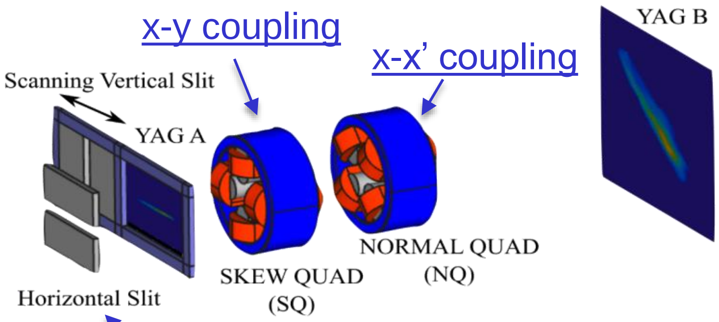
Single-shot wakefield mapping





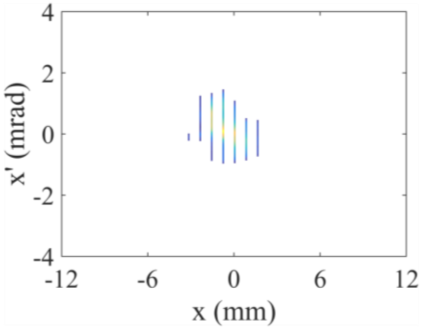


Single-shot Transverse phase space measurement

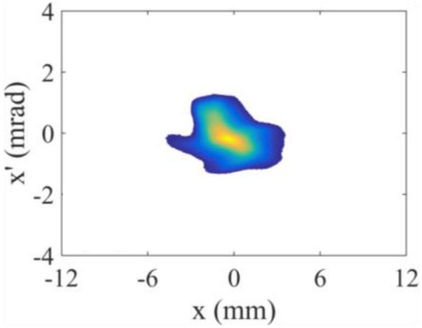


Minimizing y-y'

Slit-scan result



Projection result

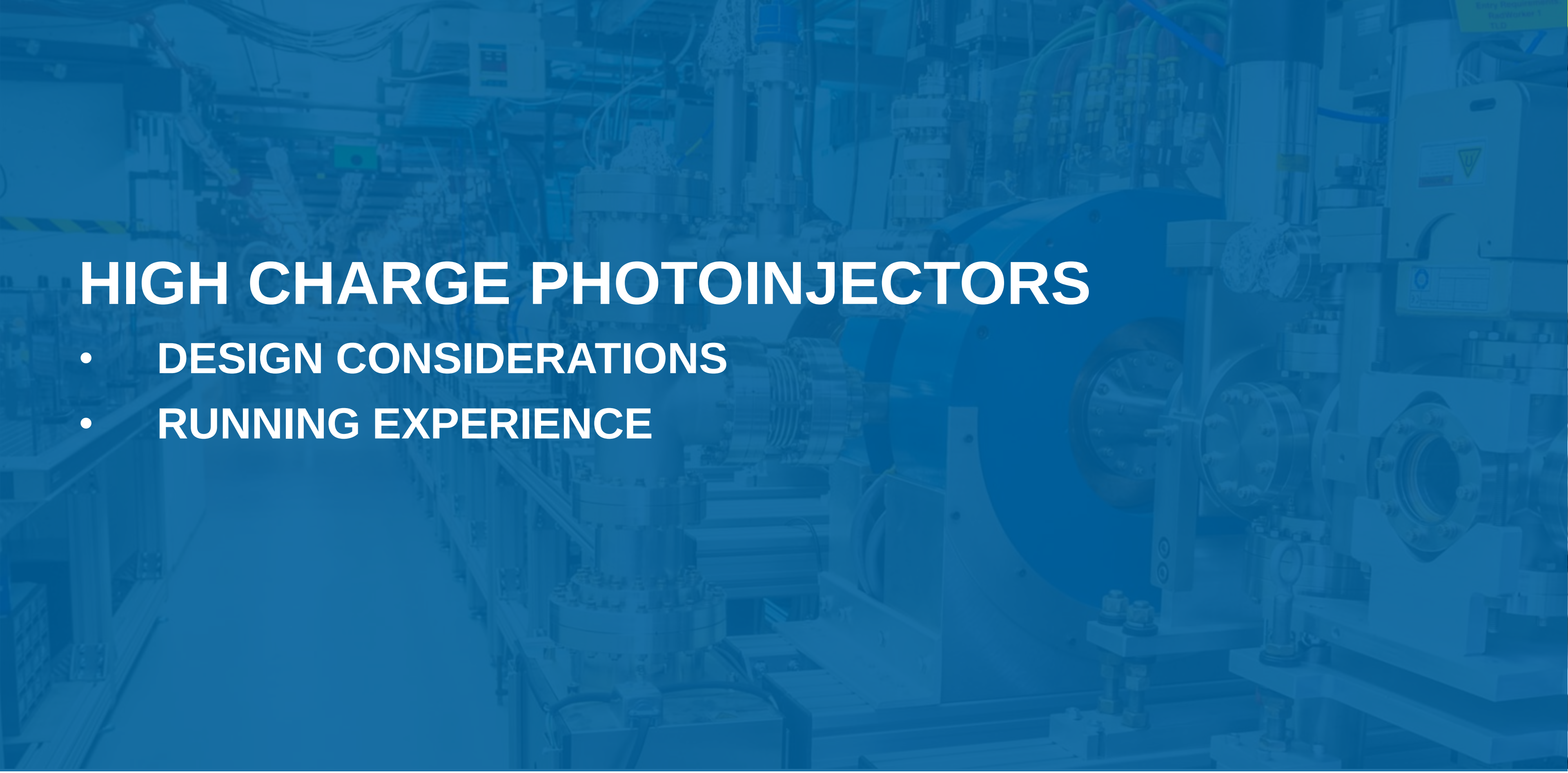


10 spot ×100 shots × 2 Hz
→ 500 s for avg image

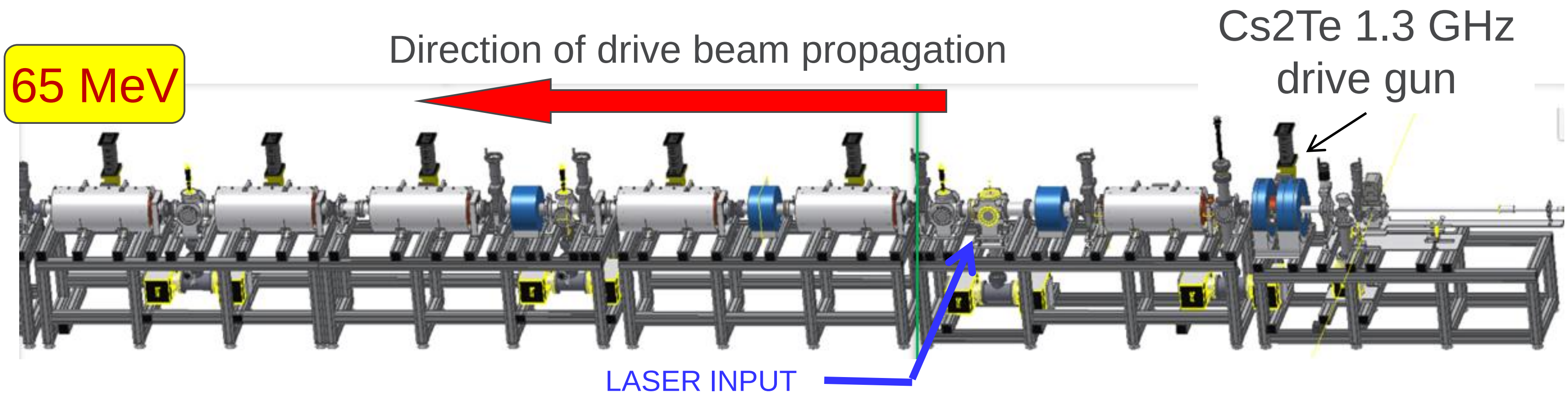
Getting image of each shots

HIGH CHARGE PHOTOINJECTORS

- DESIGN CONSIDERATIONS
- RUNNING EXPERIENCE



AWA HIGH CHARGE DRIVE PHOTOINJECTOR



- **Gun design considerations**
  - Avoid laser damage of photocathode
  - Avoid Space Charge limited emission
  - Avoid scraping laser on the way in
  - Avoid scraping electrons on the way out.
  - Minimize vacuum pressure rise
  - Minimize beam loading

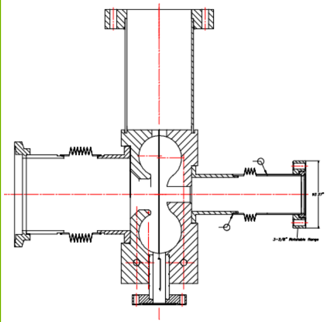
- **Acceleration cavity design considerations**
  - Minimize beam loading
  - Avoid scarping electrons
  - Minimize vacuum pressure rise

GUN DESIGN CONSIDERATIONS

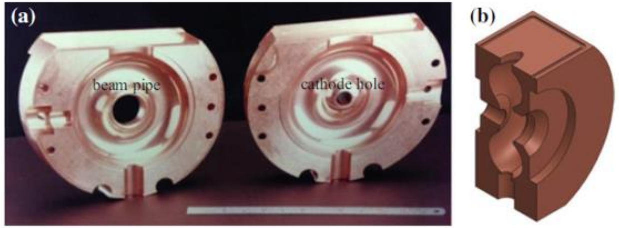
Experimental Issue

AVOID DAMAGE THRESHOLDS: EXPLOSIVE EMISSION

Original AWA drive gun



- 1995-2001
- 1,3 GHz, 0.5 cell
- re-entrant nose cones
- Ec=120MV/m (α=4)
- Mg cathode (15mm dia)
- Small laser spot.

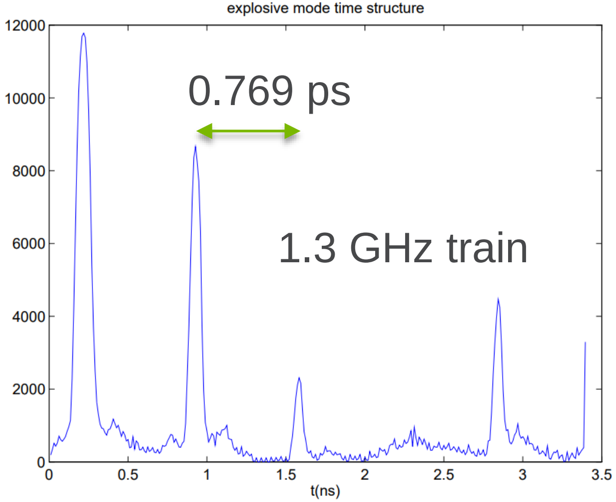


$$\alpha = \frac{eE_0}{2mc^2 k_z}$$

AWA, PAC95
https://accelconf.web.cern.ch/p95/ARTICLES/WPB/WPB11.PDF

http://accelconf.web.cern.ch/e98/PAPERS/TUP33C.PDF

(AWA, PAC95)



Q saturation
>40 nC
>MAX Q 56 nC
at 4 mJ

Limited by e- striking wall

Explosive emission when laser energy density < 10mJ/cm2 (0.1 mJ/mm2)

Need larger laser spot
Longer laser pulse?

GUN DESIGN CONSIDERATIONS

Experimental Issue

AVOID DAMAGE THRESHOLDS: LASER CLEANING

Metal	Energy Density of Cleaning Laser [mJ mm^{-2}]
Copper	1
Magnesium	0.1
Niobium	0.6
Lead	0.2

(Dowell & Rao, An Engineering Guide To Photoinjectors)
https://arxiv.org/abs/1403.7539

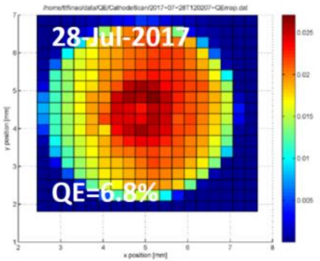
clean … without altering the surface finish

E= hν (remember)

Metals well known.
e.g. Mg: E < 10 mJ/cm2

Cs2Te?

5mm



Cs2Te?
Cathode center →
"We explain this by laser cleaning of the cathode surface"

FLASH, FEL2017
https://accelconf.web.cern.ch/fel2017/papers/wep003.pdf

FLASH

Ec = 52 MV/m (α=1.86), 1 nC ,E = 50 nJ, QE =10 %, Laser sigZ 6.5 ps (peak power of 3 kW only); Laser dia. = 1.2 mm (fluence **4.4 mJ/cm2**)

"far away from typical damage thresholds of a few J/cm2. These are all reasonable low laser power values which eases the design of the laser system and, damages or ablations of optical components or of the cathode thin film itself are avoided."

GUN DESIGN CONSIDERATIONS

simulation Issue

Avoid Space Charge (SC) limited emission

Threshold

SC field from bunch E_{RF}

$$E_{SCL} = \frac{q}{A\varepsilon_0} = \frac{\sigma}{\varepsilon_0} = E_{applied}$$

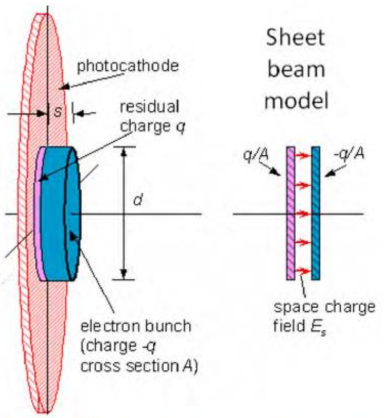
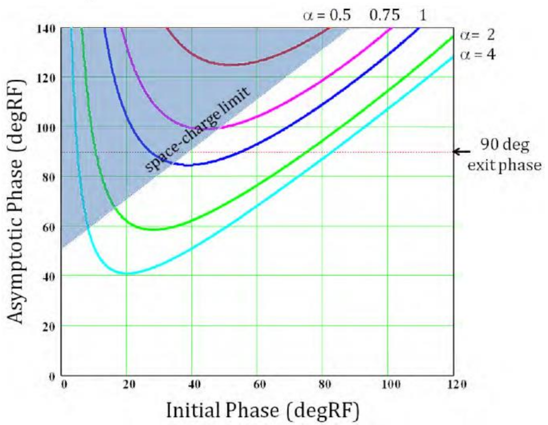


Figure 1.10. Sheet beam model for short pulse photoemission. [Courtesy of A. Vetter]

$$\sigma_{SCL} = \varepsilon_0 E_0 \sin(\phi_0)$$

$$\alpha = \frac{eE_0}{2mc^2 k_z}$$

$$\alpha \sin(\phi_{0,SCL}) = \frac{eq_{bunch}}{2\pi\varepsilon_0 k_z R_c^2\, mc^2} \qquad (1.38)$$



e.g. SC limit
Q=250 pC
Rc = 1mm

Need → Large laser spot, Longer laser pulse, High Ec, Good launch phase → Avoid e- spray (P increase)

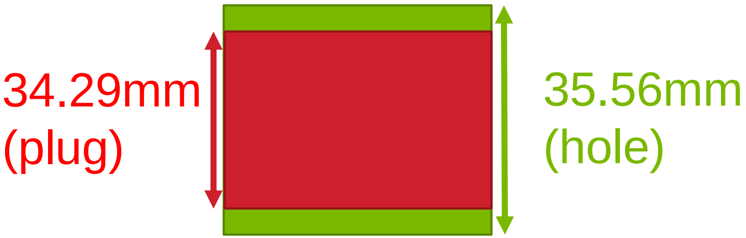
(Dowell & Rao, An Engineering Guide To Photoinjectors)
https://arxiv.org/abs/1403.7539

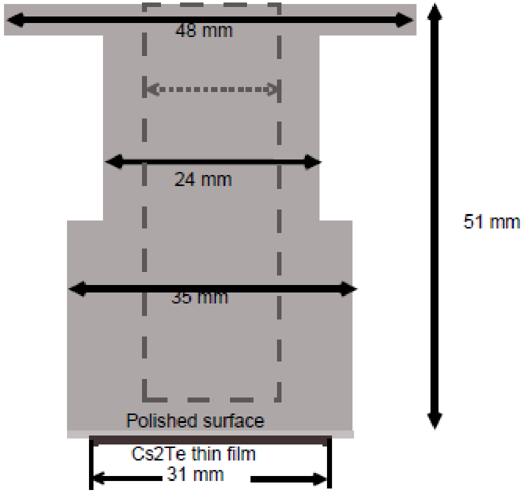
GUN DESIGN CONSIDERATIONS

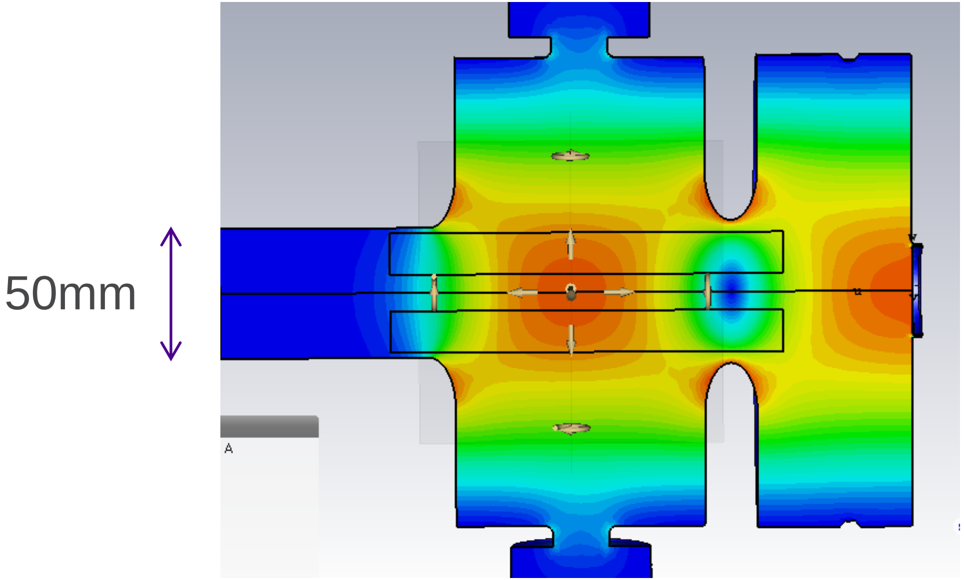
2005: Gun2 1.5 cell gun with Mg

2011: Gun2 1.5 cell gun with Cs2Te

2021: Gun3: RF symmetrized





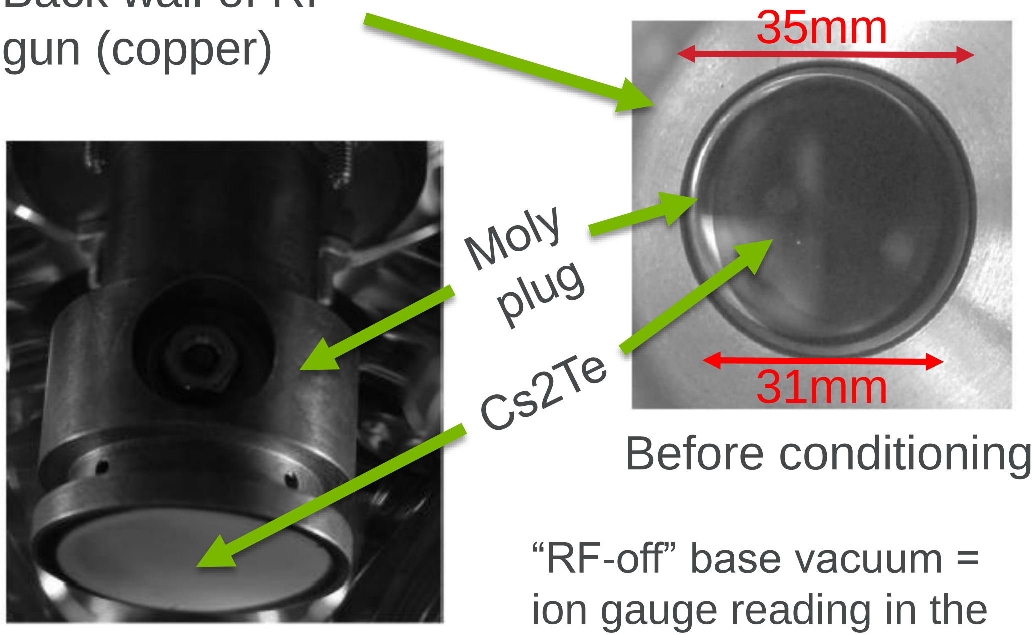


Eiris/Ecath = 1.04

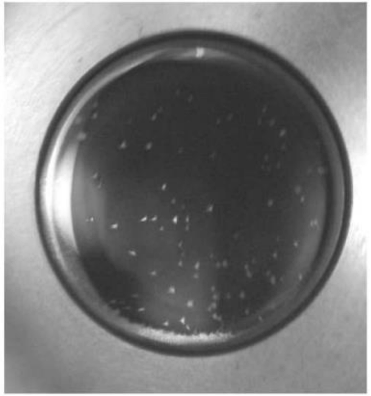
GUN DESIGN CONSIDERATIONS

Experimental Issue

AWA Cs2Te photocathode



Before conditioning



1. After: 120 hrs & 60 MV/m
   - Slow RF conditioning
   - No arcing <4 nC
   - Strong arcing >4nC, 4×10^{-9}
   - Strong arcing at "wrong" phase
2. 70 MV/m
   - Rc=22mm
   - Improved laser profile
   - No arcing 100 nC, 4×10^{-10}

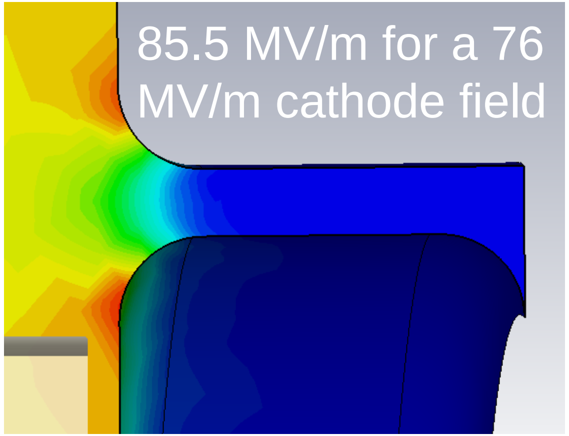
"RF-off" base vacuum = ion gauge reading in the gun was 2.0×10^{-10} Torr

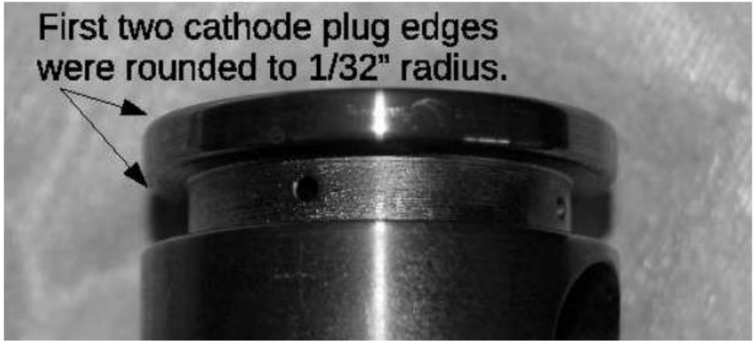
*note: gun was RF conditioned to 88 MV/m with Cu cathode

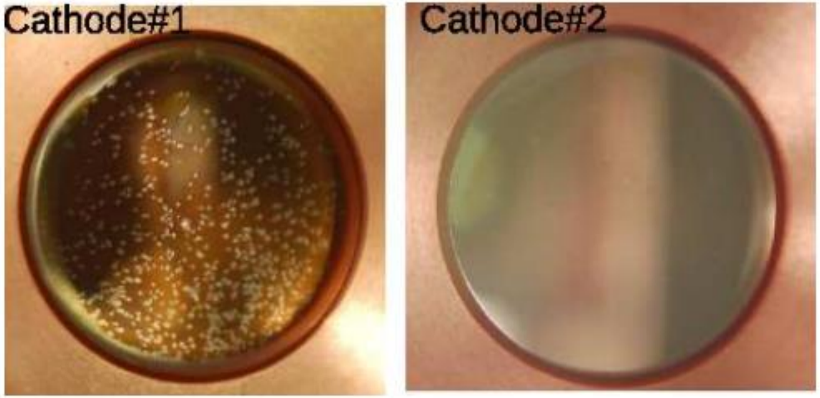
GUN DESIGN CONSIDERATIONS

Experimental Issue

Careful cathode plug design
Rounded edges to reduce arcing, less trips, less vacuum rise







After 1 year with high QE, fast RF conditioning, and no arcing problem

E. Wisniewski, NAPAC16
http://accelconf.web.cern.ch/napac2016/papers/wepob19.pdf

GUN DESIGN CONSIDERATIONS

Gun summary

Challenge: High charge means high laser energy and lots of e- spray

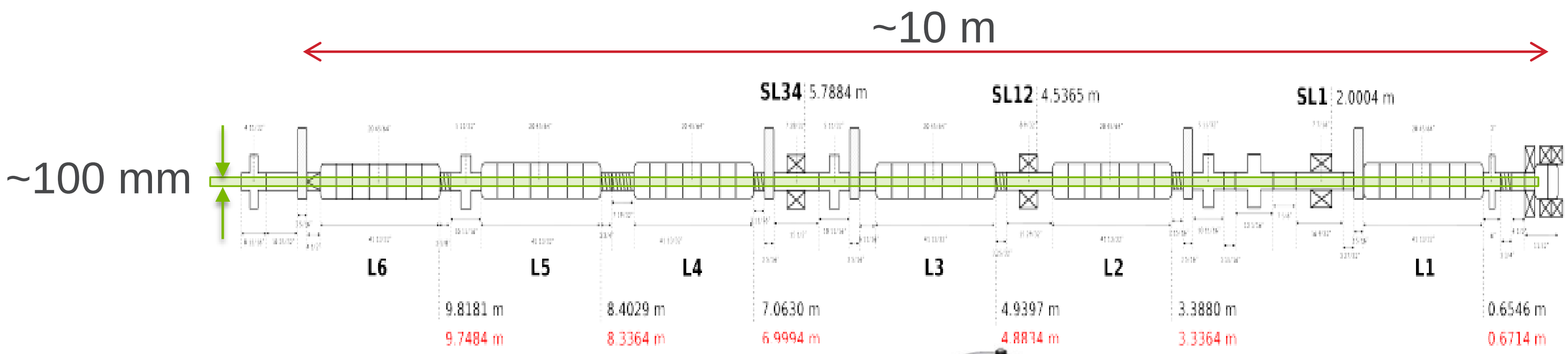
Solution:

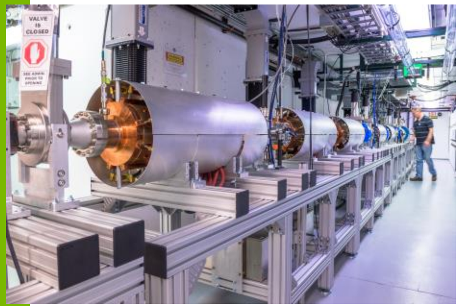
- Avoid arcing and vacuum base pressure rise
  - Arcing → Vacuum pressure burst
    - High laser intensity can cause
      - explosive emission
      - laser cleaning
    - Careful cathode plug design
  - Vacuum pressure rise → e- hitting wall
    - Halo/Spraying electrons (SC limited emission)
    - Scraping electrons on the way out.
- Beam loading? (1.3GHz stored energy = 27.2 J; Beam = 20nC*6MeV = .12J)

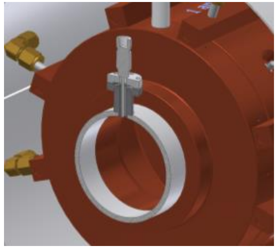
Arcing and high laser intensity:
- Need large laser diameter
- Homogenized laser

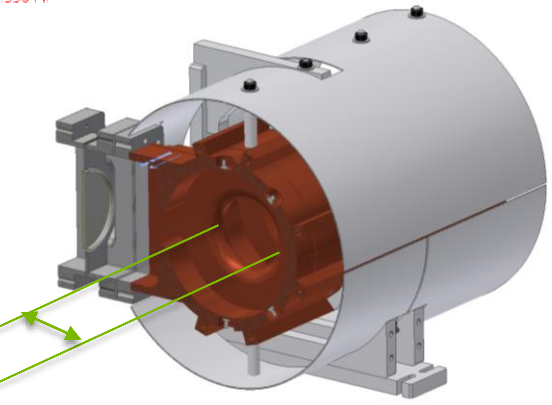
Vacuum pressure rise:
- Need high Ec field
- Need large apertures

RF CAVITY DESIGN CONSIDERATIONS







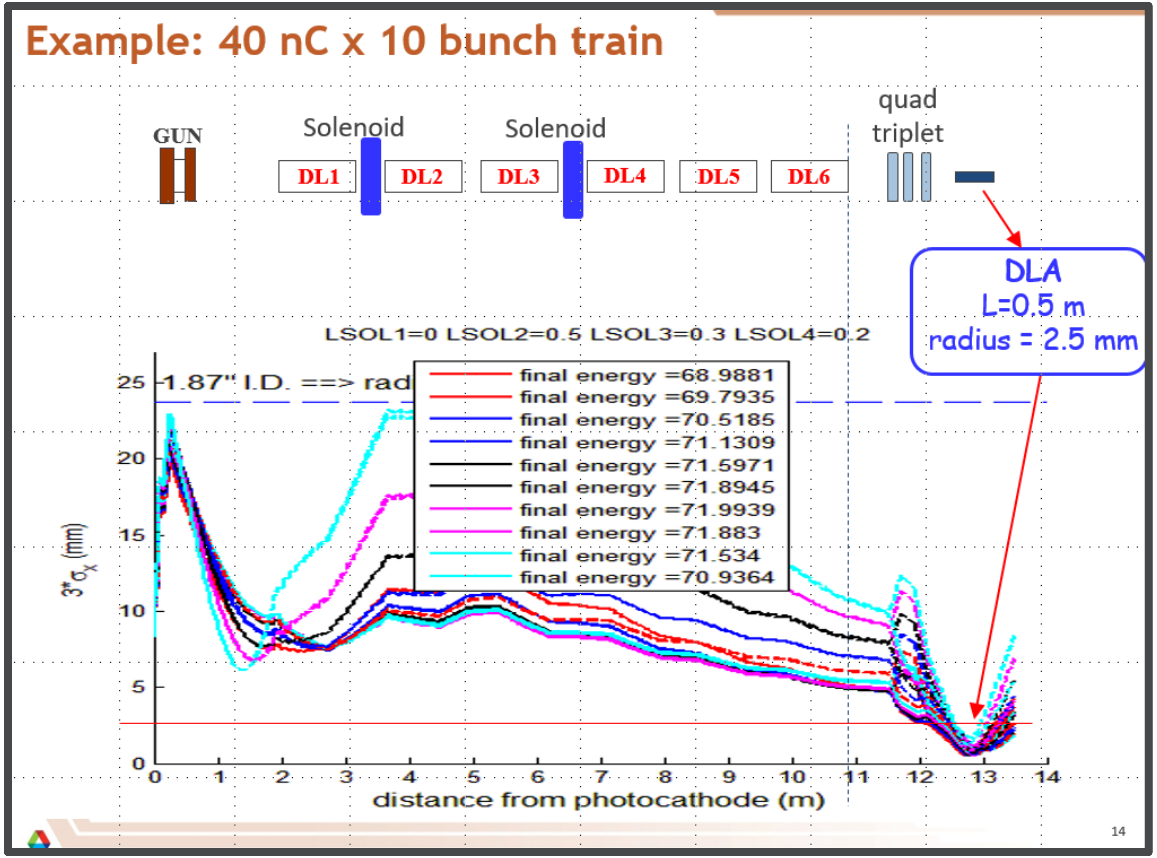


Large IRIS

- Low wakefield
- Low Shunt Impedace
- Minimize e- scraping

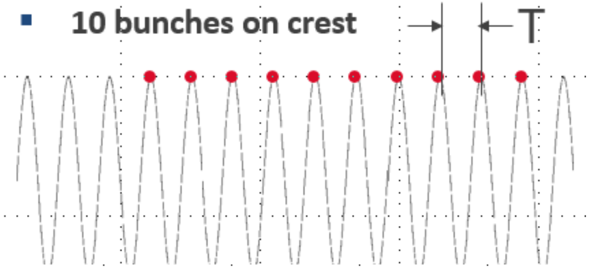
High Stored Energy helps with beam loading for ultra-short pulse trains

MULTIBUNCH WAKEFIELD EFFECTS AND ITS MITIGATION

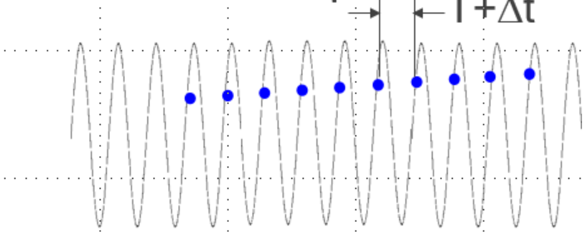


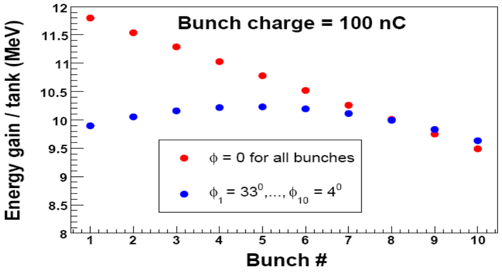
Compensate with stored energy.

- 10 bunches on crest



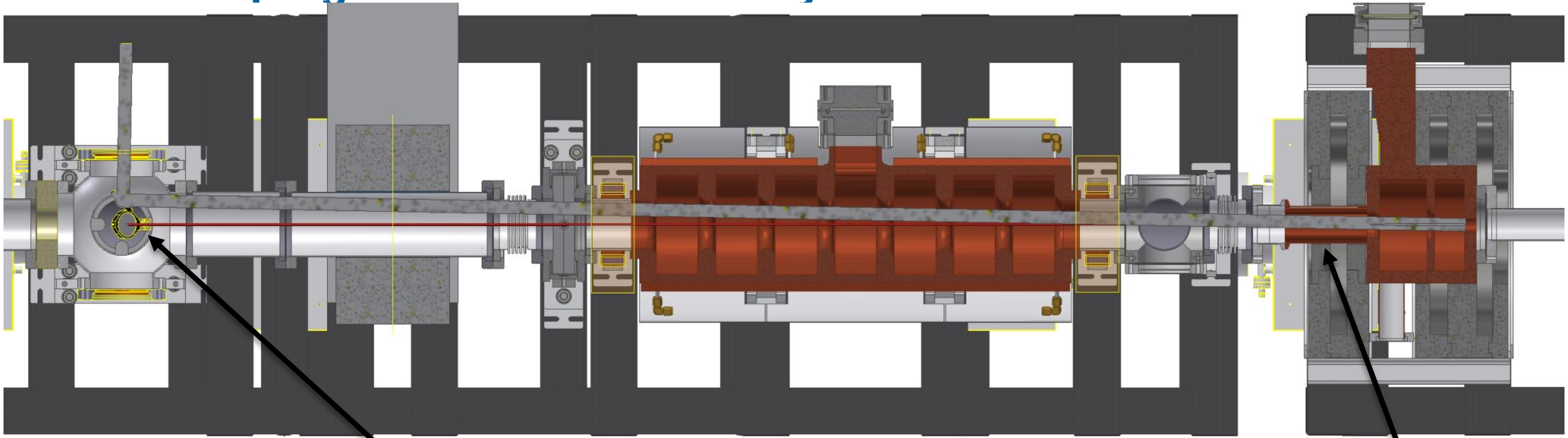
- Bunches at different phases



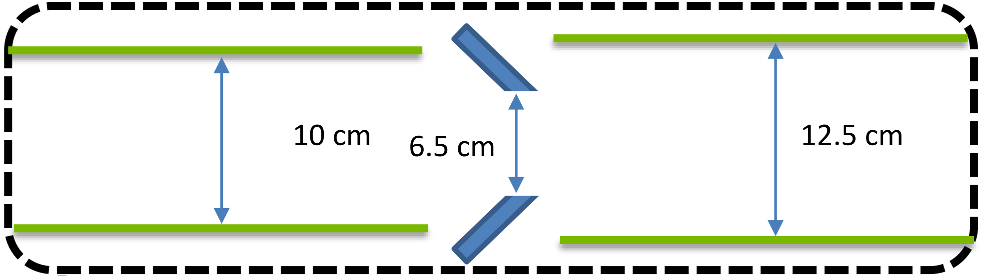


AWA LARGE APERTURES

Avoid scraping laser on the way in (allows for large laser spot)
Avoid scraping electrons on the way out

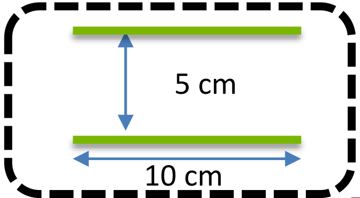


Laser input mirrors



>10cm
2 exceptions

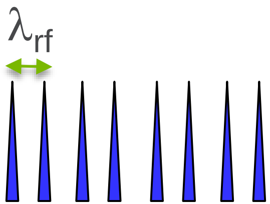
Gun exit pipe

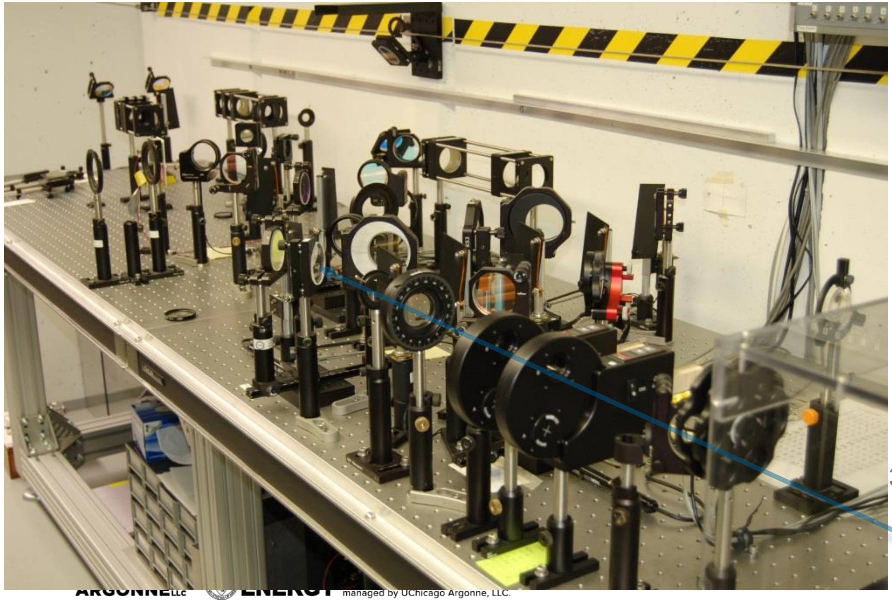


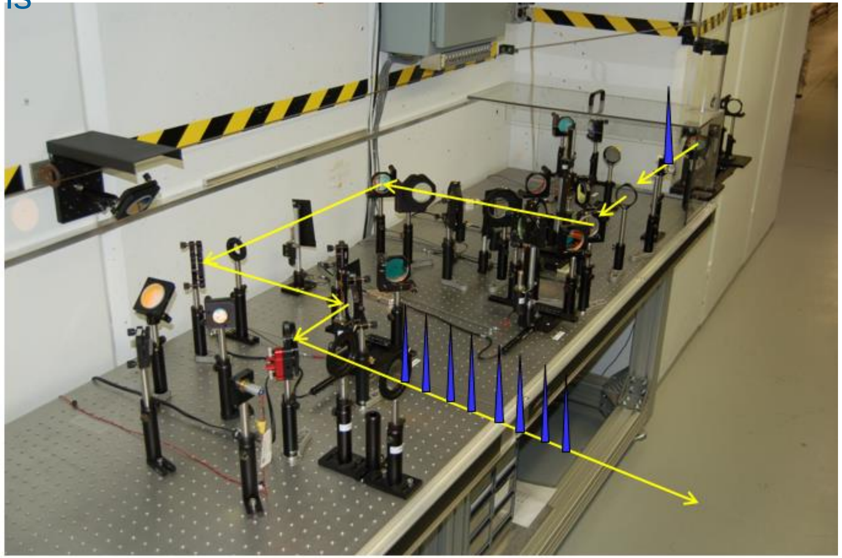
AWA LASER INPUT

Laser Multisplitter (50-50 beam splitters, waveplates, attenuators

Developed in house using off-the-shelf parts
- selectable bunches and combinations
- delay stages
- alignment capability for individual delay leg
- selectable charge from 10 pC to 100 nC
- Generation of single, 2, 4, 8, 16 or 32 bunch trains



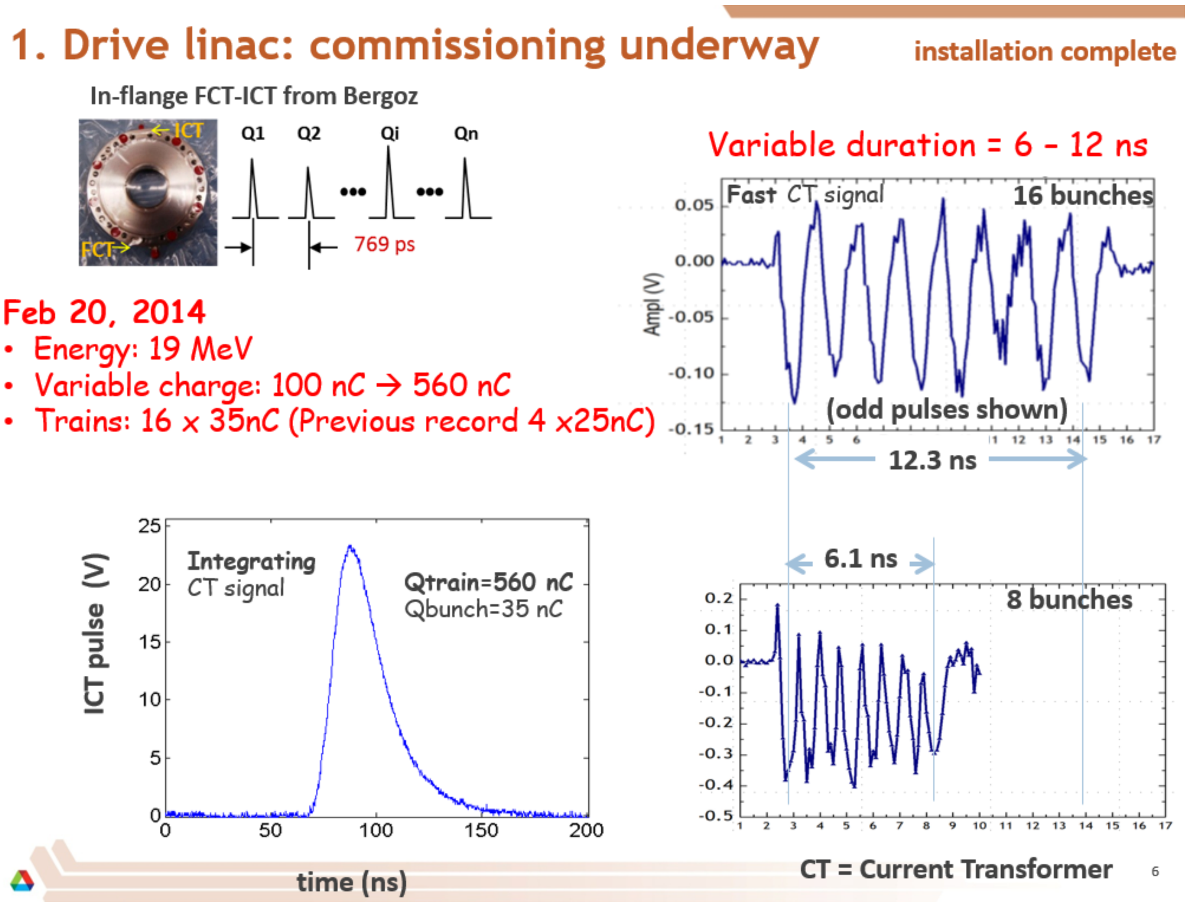




Laser input path

AWA PHOTOINJECTOR PERFORMANCE

DOE Review 2015



<u>Lesson learned:</u>

High charge propagation is vacuum limited

<u>Improvements:</u>

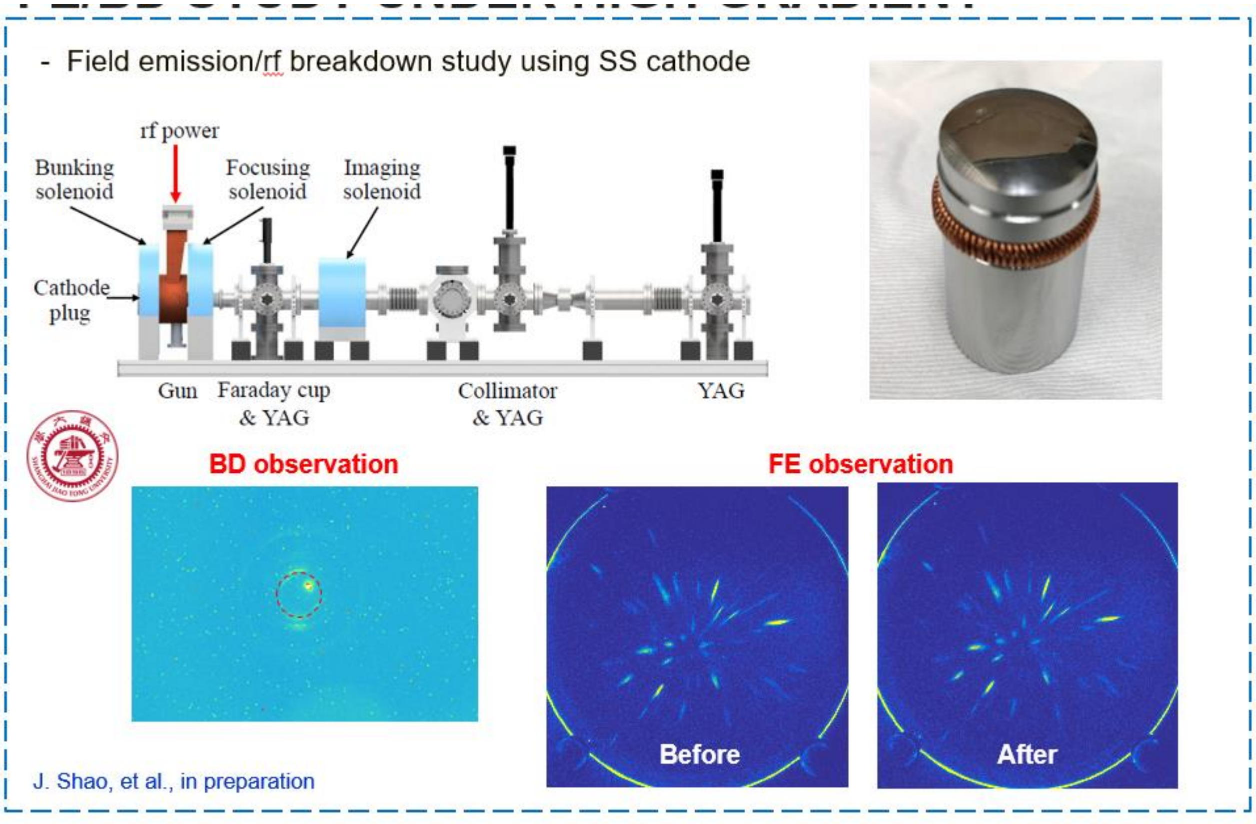
- beam alignment,
- laser alignment,
- laser profile
- Install getter pumps

<u>Current AWA record</u>

- 660 nC
- 8x82nC in 6.25 ns
- 5.2 J Gun, 6.6 J Cavity
- 100nC, 25 kA

AWA L-BAND TEST STAND

Testing photocathodes and field emission



700 MV/m

Field emission

- **Stored energy dependence**
- **In-situ field emission imaging**
- **In-situ BD location observation**

J. Shao, et al, PRL 115, 264802 (2015)
J. Shao, et al, PRL 117, 084801 (2016)

INJECTOR COMPARISON

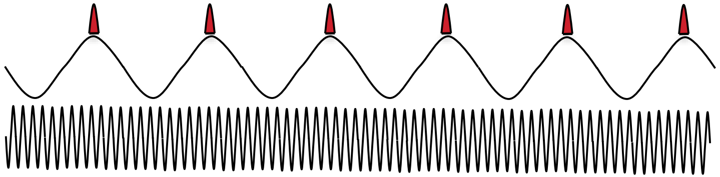
S. Döbert, CERN; PHIN S-band photoinjector, EPAC 2006
(told me they achieved 60nC om S-band)

AWA

- 1.3 Ghz L-band photocathode & L-band linac
- Cathode diameter = 31mm
- microbunch Q = 160 nC
- Train = 8x82nC (660 nC, 6.25 ns)
- G4 at AWA will be ~27.2 J
- Beam = 5.2 J Gun (19%)
- Last bunch in train probably create halo do to drop in Ec due to beamloading

PETRA IV

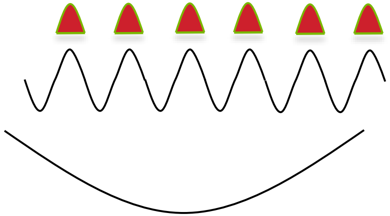
- 3 Ghz S-band photocathode & S-band linac
- Cathode diameter = ?
- microbunch Q = 22 nC
- Train = 6x7.5nC (45 nC, 1.67 ns)
- Stored energy of the S-band gun at Tsinghua is ~1.8 J
- Beam = 45nC*6MeV = .27J (15%)
- Energy droop in train → affects transport



8x82 = 660nC

1.3 GHz

13 GHz



6x7.5 = 45nC

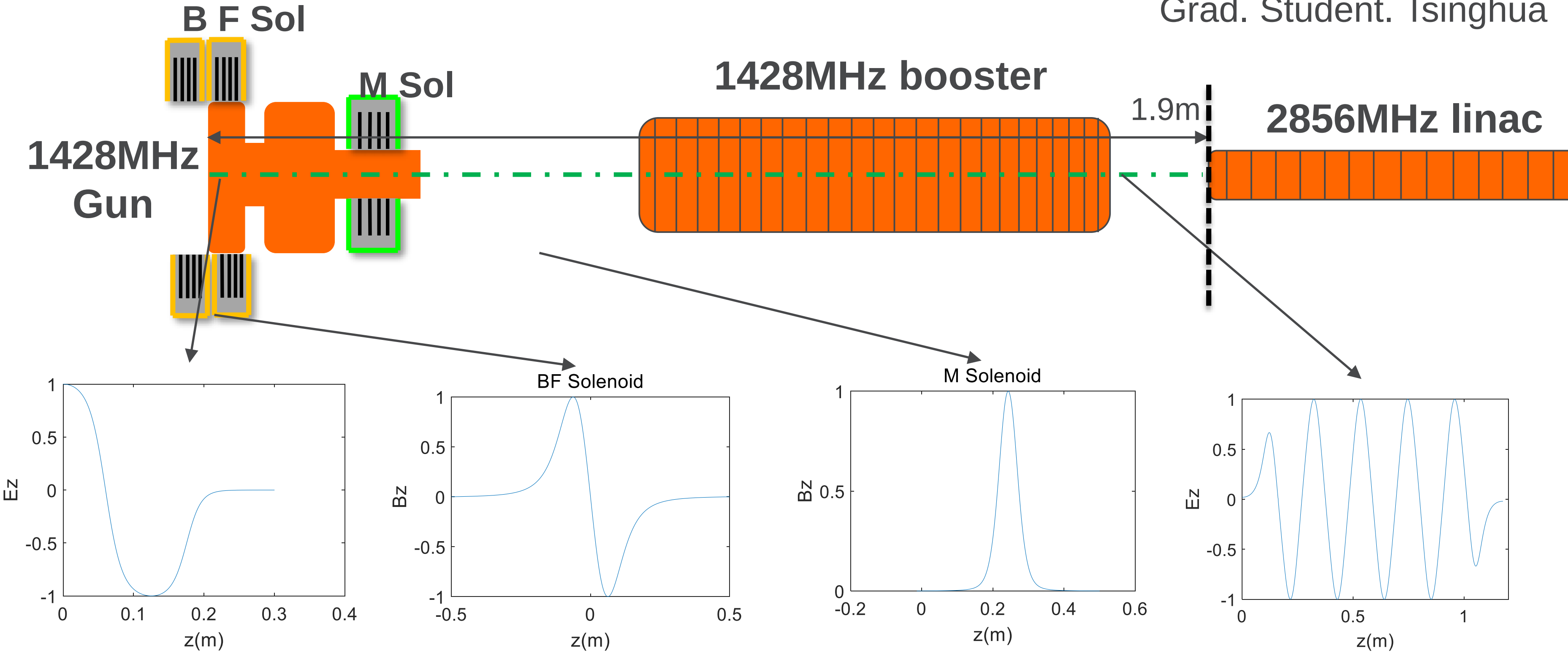
3 GHz

0.5 GHz

EXAMPLE OF 20 NC INJECTOR FOR APS

PREVIOUS DESIGN STUDY FOR 20NC INJECTION INTO APS BOOSTER

Simulations: Han Chen
Grad. Student. Tsinghua

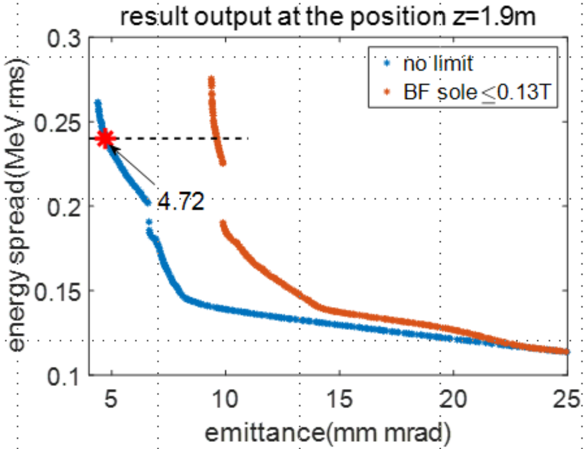


OPTIMIZATION SETTINGS

I use a NSGA-II genetic algorithm and ASTRA to optimize and simulate the beam dynamics. Some settings are as the followings.

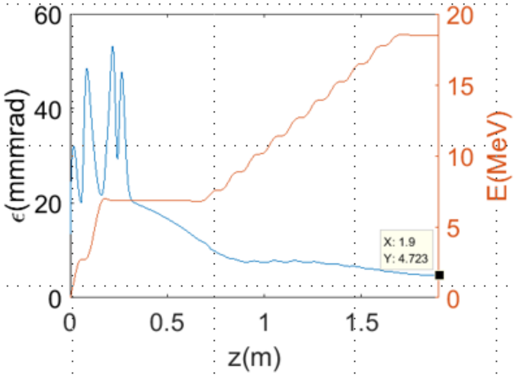
- Thermal emittance 0.75mmmrad/mm, Charge 20nC
- Uniform transverse distribution, 20ps FWHM flattop laser pulse, rising time of 2ps
- Maximum field in the gun is 70MV/m, energy gain about 7MeV
- Maximum field in the linac is 25MV/m, energy gain about 12MeV
- The center of BF solenoid is the cathode surface.
- The center of M solenoid is set to be about 0.25m, taking installation space into consideration.

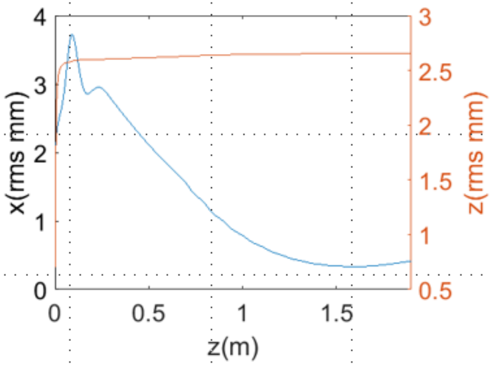
Typical example of simulation results

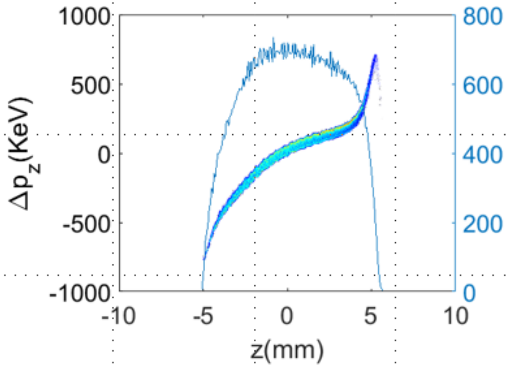


laser pulse length	20 ps	BF solenoid strength	0.2291T
beamsize	2.0287 mm(rms)	M solenoid strength	0.3260T
emission phase	-5.1123	position of the linac	0.6 m

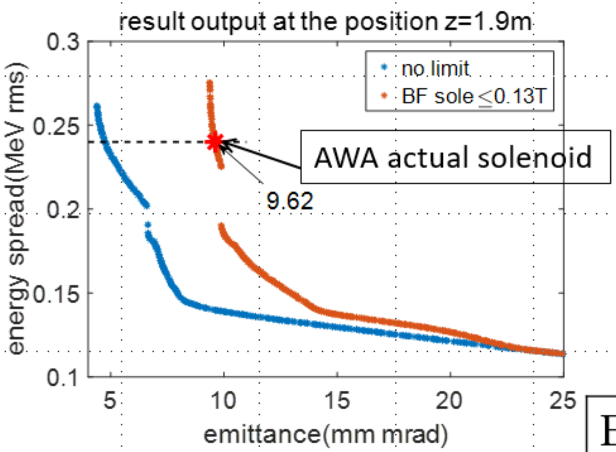
Emittance	4.72 mmmrad	Energy spread	0.241MeV(rms)





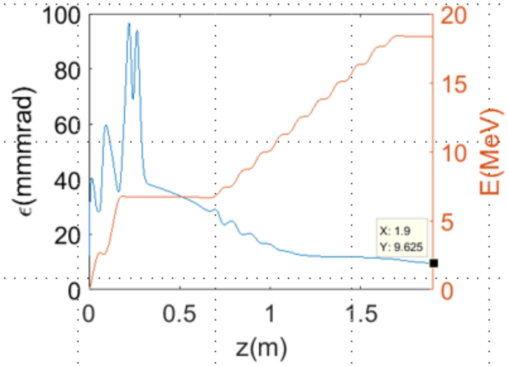


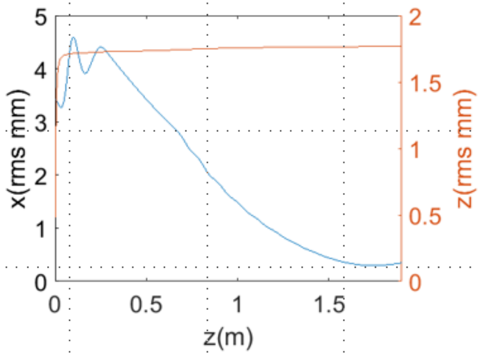
Typical example of simulation results

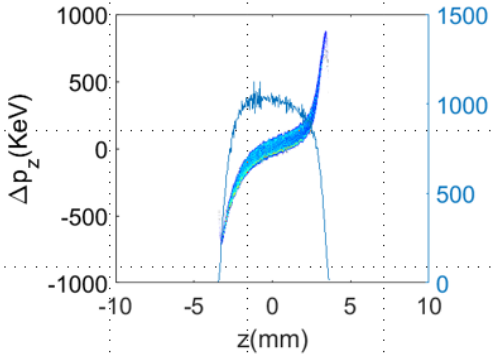


laser pulse length	20 ps	BF solenoid strength	0.13T
beamsize	3.4289 mm(rms)	M solenoid strength	0.3862 T
emission phase	-20	position of the linac	0.6 m

Emittance	9.62 mmmrad	Energy spread	0.240MeV(rms)







SUMMARY & DISCUSSION

SUMMARY: HIGH Q ISSUES

- Vacuum
  - AWA high Q operation is vacuum limited (base pressure tripping and arcing)
  - Avoid electrons hitting the wall
    - Halo and SC limited emission
    - Laser, use multi-splitter instead of 2ns laser
  - Lots of pumping
  - Avoid laser ablation (explosive emission & laser cleaning)
- Beam dynamics
  - large transverse laser spot & long laser pulse, therefore, higher emittance
  - Optimize for low electron loss with acceptable beam parameters for booster
  - Minimize beam loading (Design issue)
    - Over-coupled beta will not help with short train
    - beam loading compensation
      - Frequency or Time domain compensation
      - AWA: High Stored Energy: Adjust launch phase so each bunch “sees” ~same Ec
- Radiation?
  - low rep rate so AWA is not limited by radiation.
  - PETRA-IV is also low rep rate (2 Hz) so probably no radiation issues

SUMMARY: PRACTICAL CONSIDERATIONS

- **LASER**
  - Use large laser transverse spot → Need large diameter photocathode
  - Maximize clearance for injection of large laser spot (from input mirror to photocathode)
    - AWA >10cm except two tight spots, gun exit pipe and laser input mirror
  - Move laser input mirror far off axis (Distance between laser input mirrors: gap = 6.35 cm)
  - Use long laser pulse. (*Probably, Lacking experimental data,)*
  - Avoid hot spots in laser
- **GUN**
  - High Ec field & phase far from e- loss (AWA student thesis: “right” phase = 55-85)
  - Large photocathode
  - Large aperture on gun iris; Gun exit pipe (length= 10cm): dia.=5cm
- **LINAC**
  - Large diameter irises and beam pipes
- **SIMULATIONS**
  - Good tools available for single beam, but we need a way to simulate beam bunch trains (RF period)
    - SC, CSR, short range wake, AND <u>long range wake</u>, Several codes have the first 3 but cannot add in the long range wake (many RF periods) while keeping SC mesh etc.