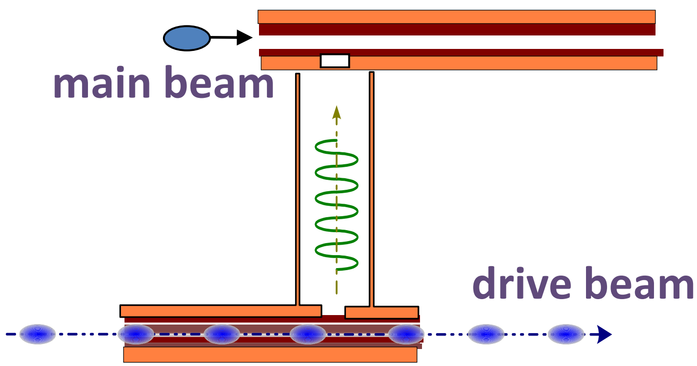
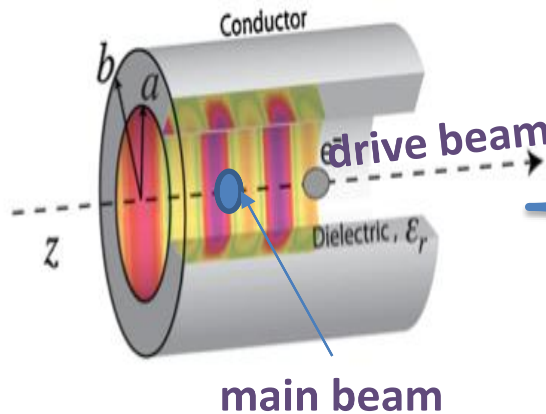
Structure-based **W**akefield **A**cceleration (SWFA)

Co-leaders: Philippe Piot (FNAL/NIU) and Paolo Craievich (PSI)

WG3

- Two general schemes:
  - **T**wo-**B**eam **A**cceleration (TBA)
  - **C**ollinear-**W**akefield **A**cceleration (CWA)





- 10 GHz-1 THz
- Cylindrical vs. Planar
- Dielectric vs. Metallic

- Efficient drive beam generation
  - 50% wall-plug to drive beam eff (Klystron-based)
  - Longitudinal Bunch Shaping has become very active area
- Staging demonstrated in TBA
- Scheme can accelerate e- and e+ (using e- drive)
- GV/m field pushes frequency towards higher frequency (shunt impedance).

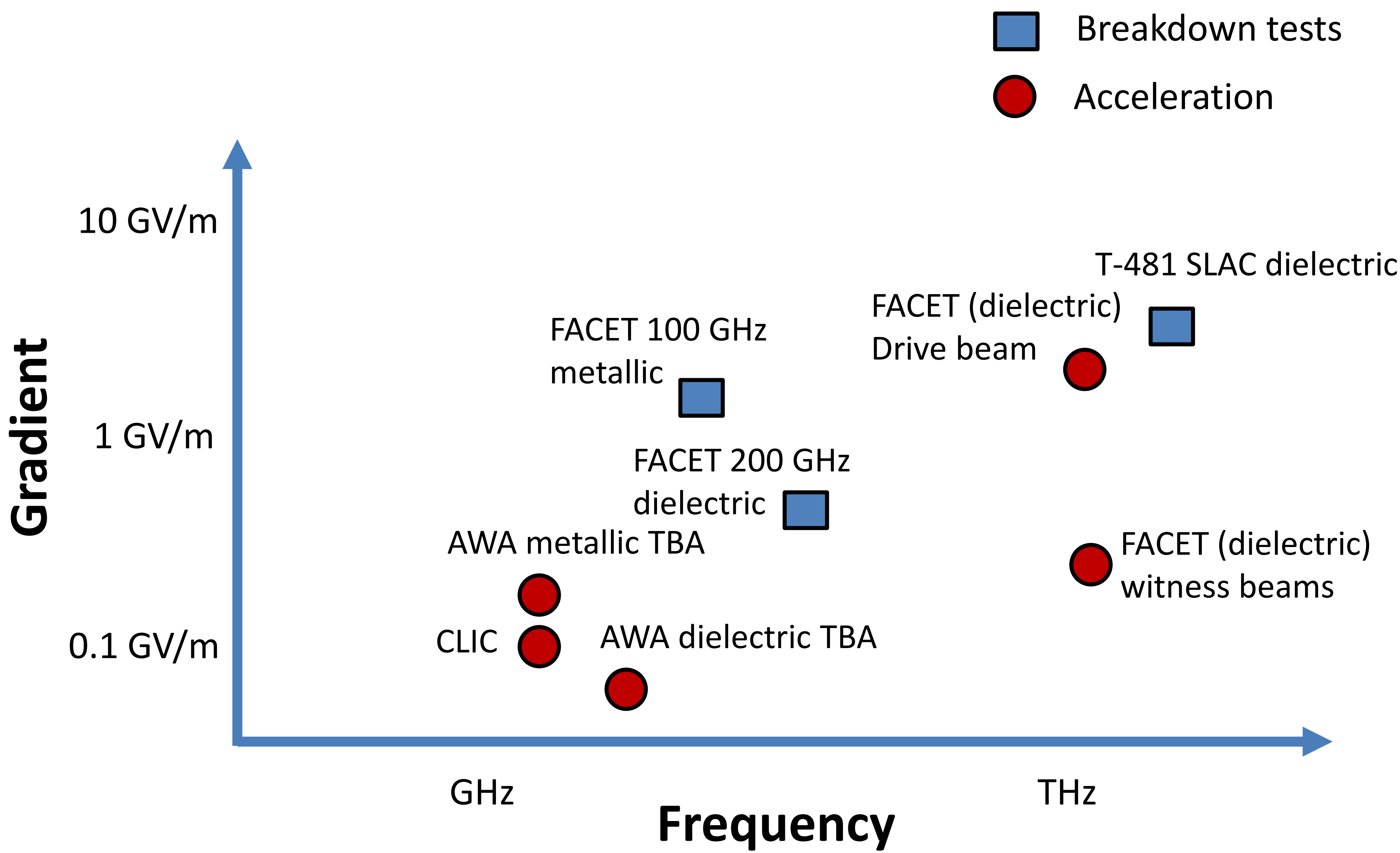
Outline

- State-of-the-art
  - Structures
  - Drive beam dynamics
  - Main beam dynamics
  - Staging
- Roadmap
  - Structures
  - Drive beam dynamics
  - Main beam dynamics
  - Staging
- Facilities and Synergy
- Conclusion

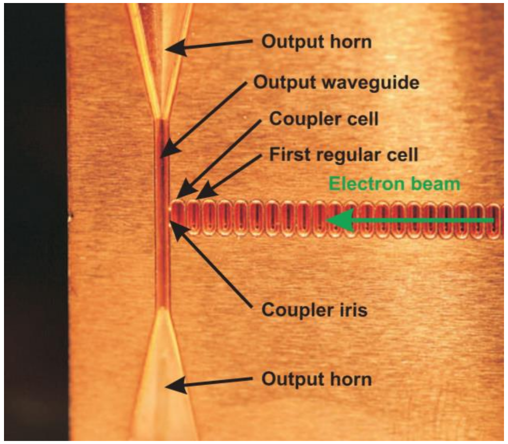
State of the Art

Structure Based Wakefield Acceleration

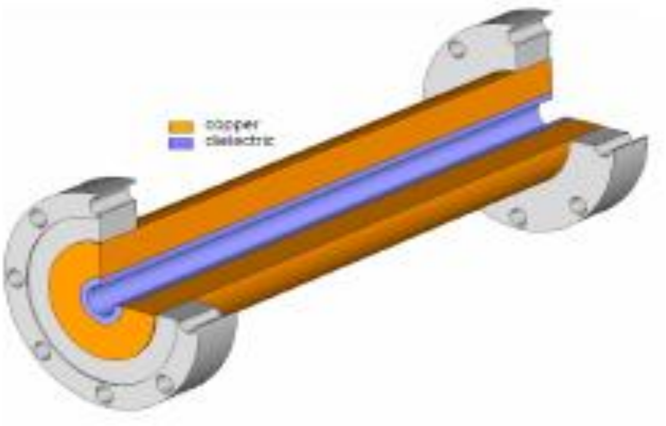
Structure Experimental Status



Structures tested

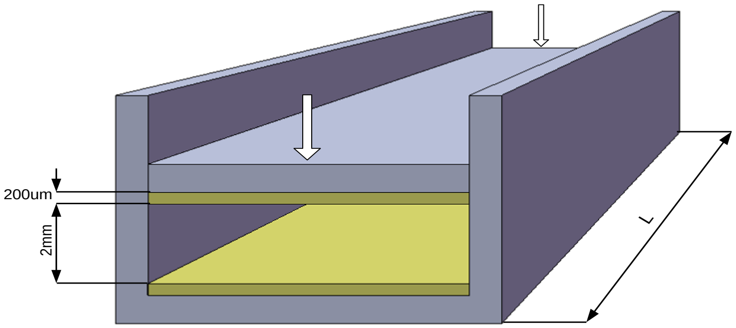


metallic planar structures



Dielectric Cylindrical

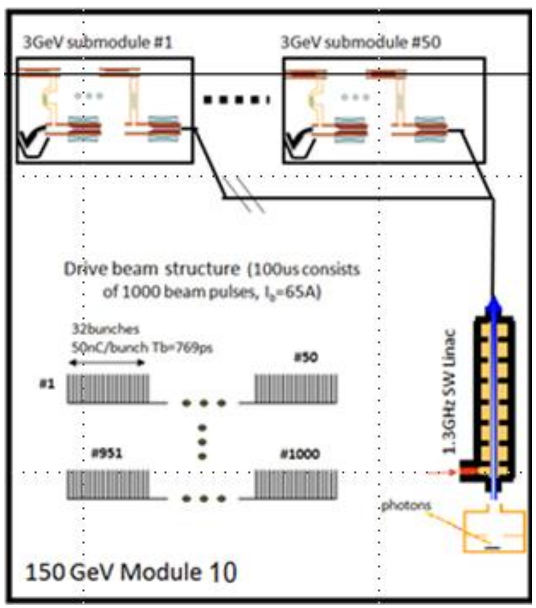
Dielectric Planar structures



Drive-beam Dynamics (I)

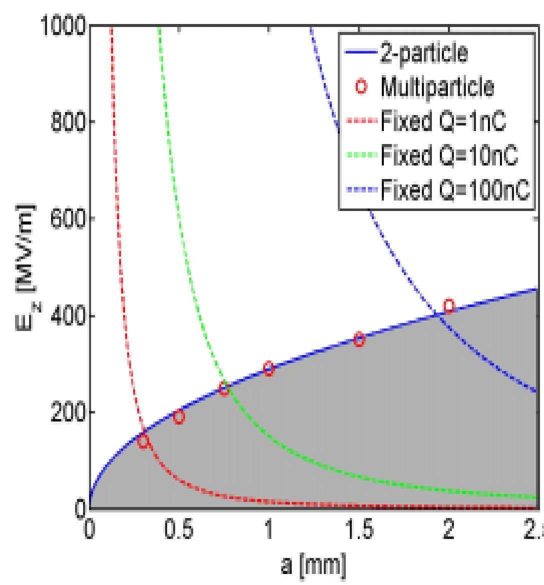
Drive-beam source technology

- GHz-scale structures → **mature**



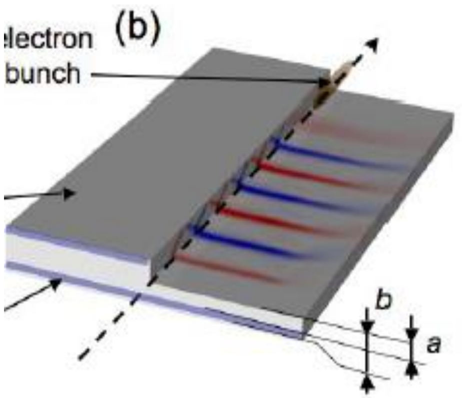
- THz-scale structures → **can leverage on FEL-injector R&D.**

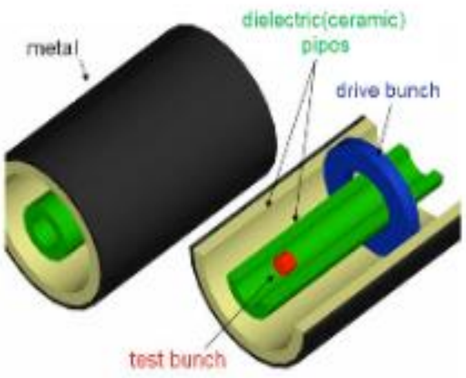
- THz-scale structures →
- **Single-bunch beam-break up (BBU) instability** for drive beam has been studied for cylindrical structures, experimental demonstration planned.



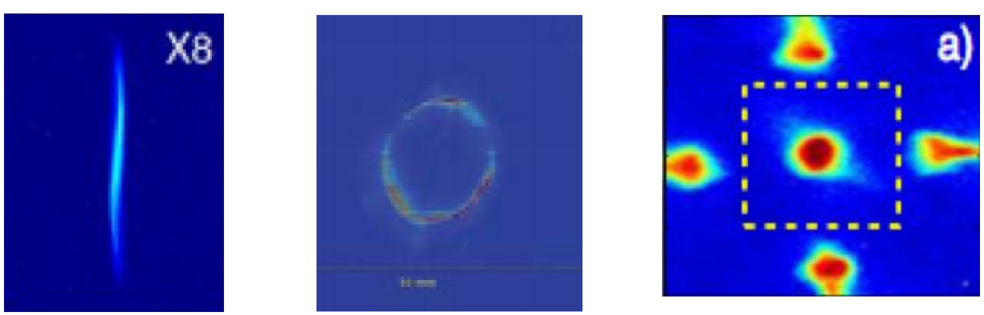
Drive-beam Dynamics (II)

- **Transverse shaping methods to match structure geometry:**
  - Multibeam/coaxial beam demonstrated
  - flat beam with ε ratio (100:1) produced at 0.5 nC





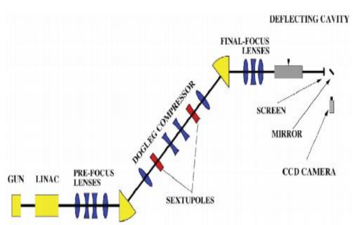
Structure Geometry



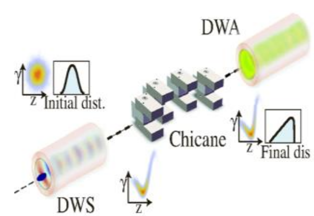
Measured e-beam profile

Drive-beam Dynamics (II)

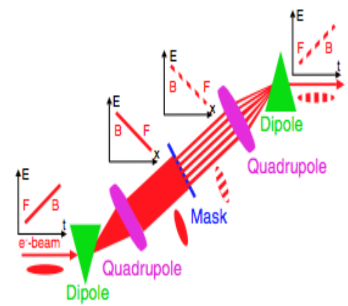
- **Longitudinal shaping methods for high transformer ratio:**
  - Field of intense research
  - proof of principle experiments carried at various facilities
  - Methods include cathode laser shaping, phase-space manipulation/exchange,…



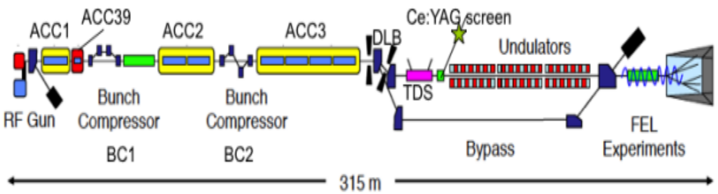
Higher-order beamline



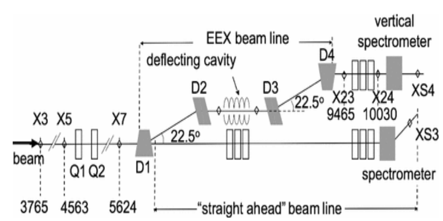
Passive energy modulation



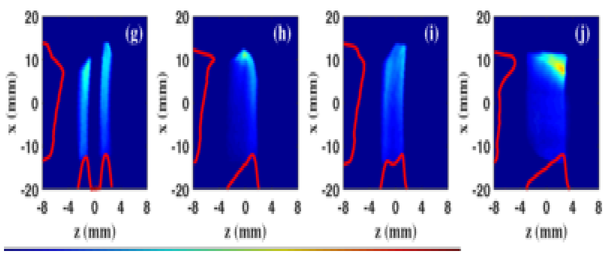
Dispersive/mask



Two-frequency



Emittance exchange

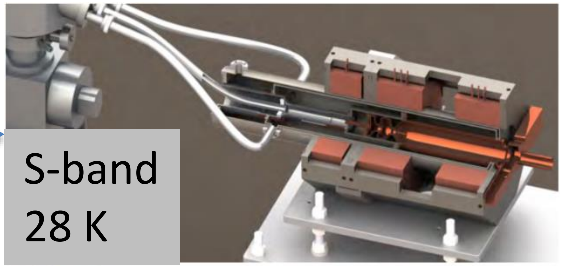


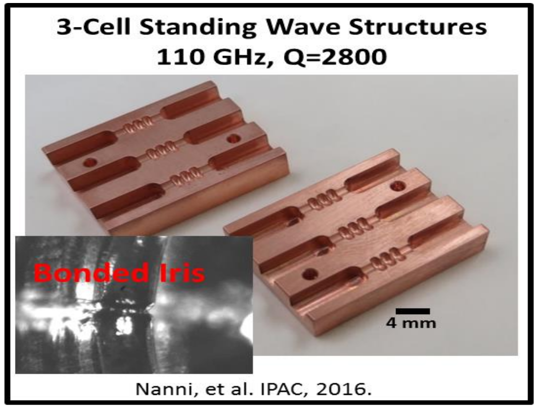
Arbitrary Shaping

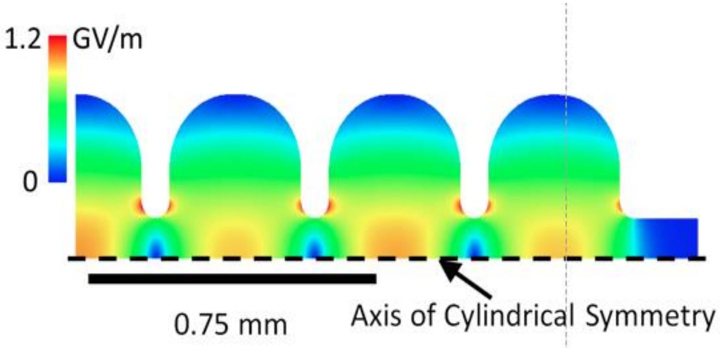
Main Beam dynamics

- TBA: GHz-scale, Dielectric/metallic, cylindrical:
  - e- : high-quality e- acceleration demonstrated (150 MV/m)
  - e+ sources can take advantage of CLIC main beam development
  - 10-100 GHz e-/e+ sources can take advantage of CLIC main beam development

- 100GHz - 1THz e- sources (need lower Q, higher repetition rate)
  - e- can take advantage of recent light-source R&D
    - S-band to X-band conventional injector
    - SRF high-current capability
  - Cryo-cooled (top) RF gun
    - high-rep rate?
  - THz RF photocathode gun
    - 3 cell structure fabricated
    - Optical rectification (LiNb) generation of THz, door-knob coupler

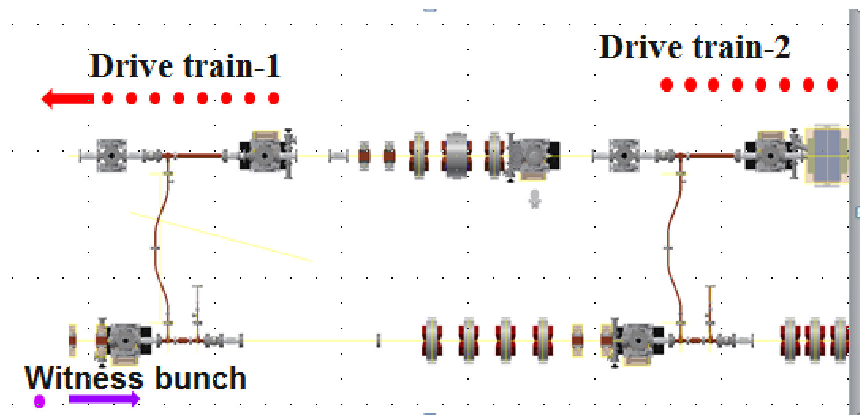


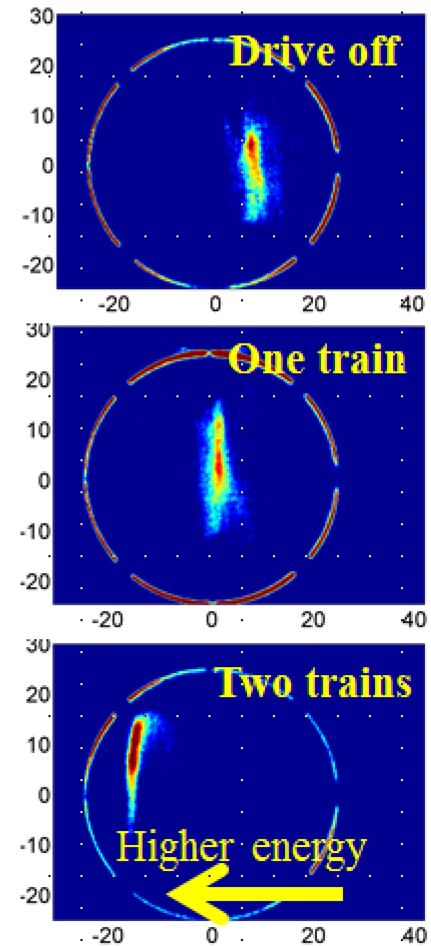




Staging

- TBA
  - Demonstrated: 11.7 GHz, Dielectric, cylindrical at AWA facility





- CWA
  - No collinear wakefield accelerator has been staged to date.

Roadmap

Structure Based Wakefield Acceleration

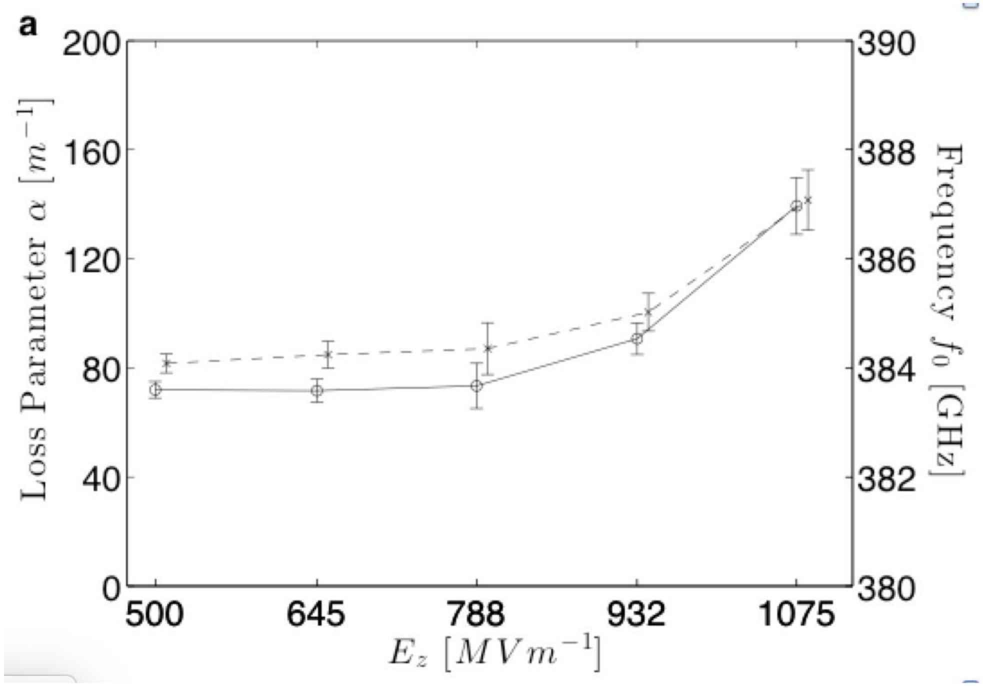
Structure

- High field (>GV/m) induced conductivity from band distortions → "**metallization**" through non-adiabatic process (collisions)

Detailed comparison to theoretical model needed

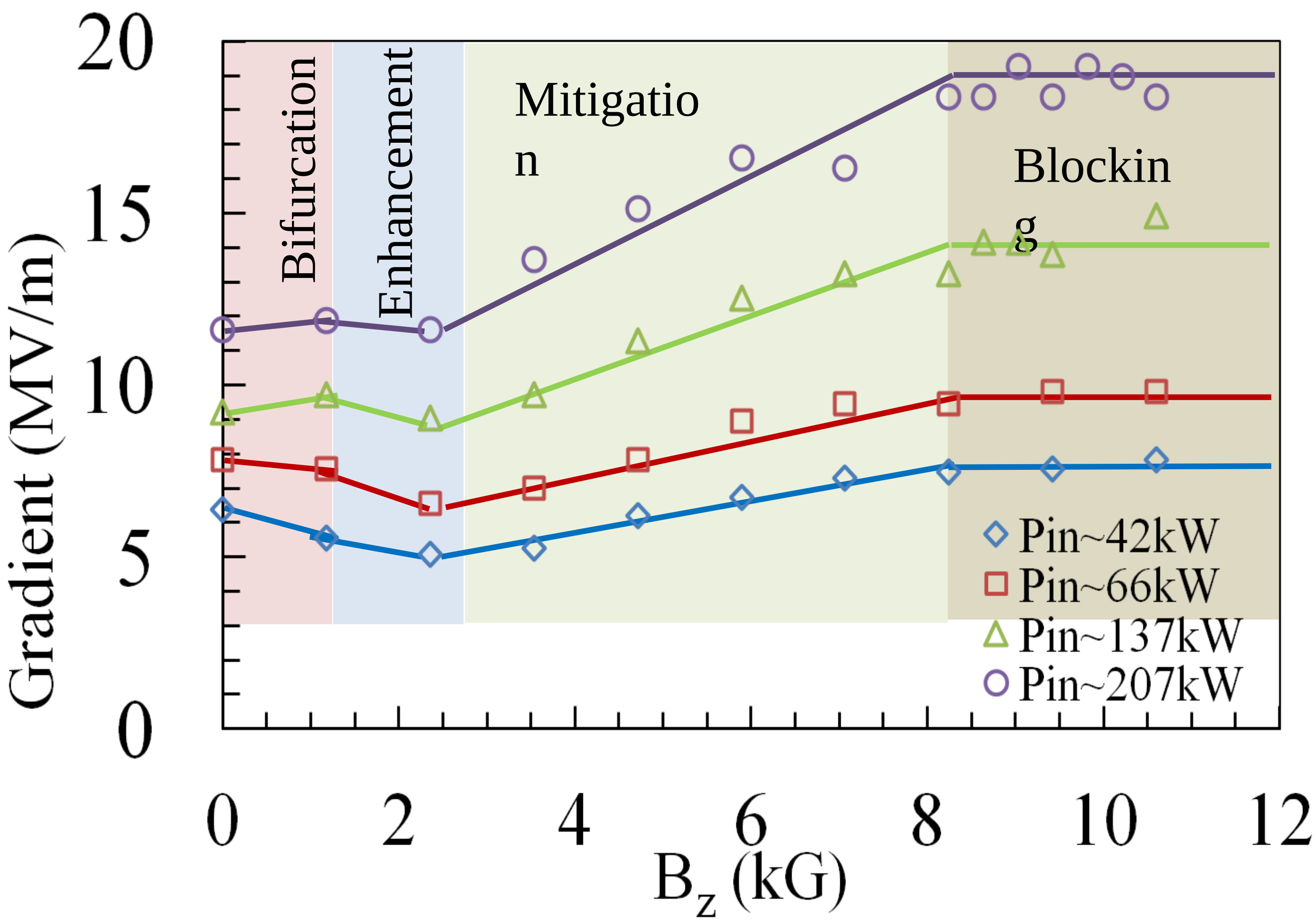
Implications for dielectric accelerator design:

1. Field exclusion from dielectric
2. Material choice



Multipactor in long pulse dielectric structures

Multipactor suppressed with Solenoid Field for a DLA



Continue to investigate other Multipactor suppression methods

Novel structure designs

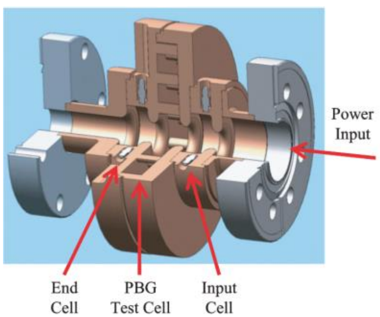
(high gradient, HOM suppression, high efficiency, …)

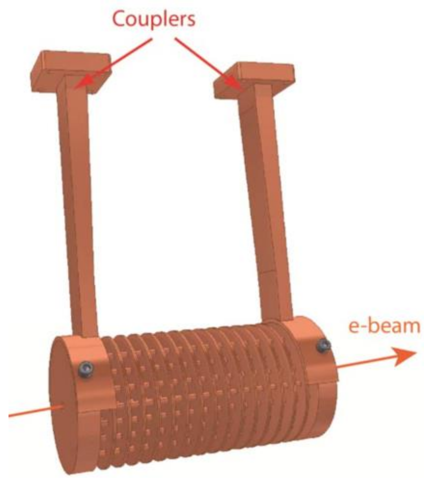
Photonic band gap structures

damping of HOM

MIT 17.1 GHz, 35MV/m, recently higher gradient 150MV/m with breakdown rate ~1

high rep rate

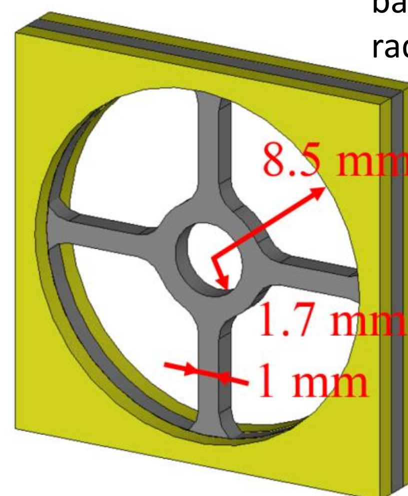




Metamaterial "wagon" wheel structure

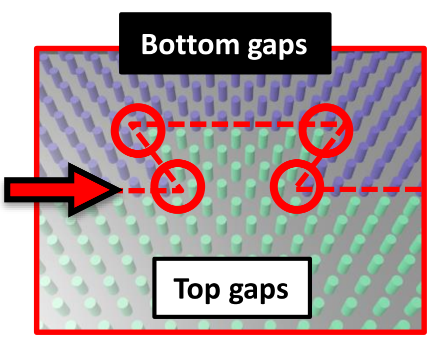
Unit cell design

Negative group velocity, backward Cherenkov radiation



Grey: stainless steel, 1 mm thick
Yellow: copper

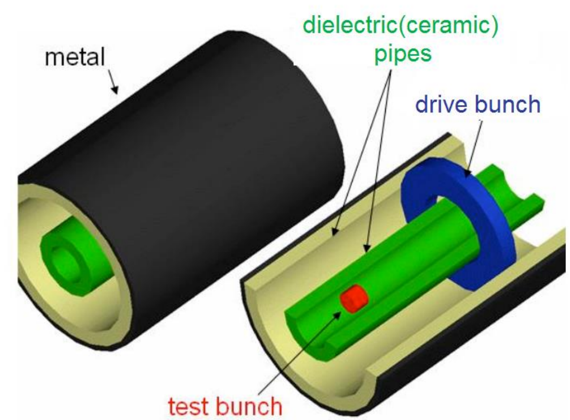
Robust Surface Wave Transportation



TPSW propagates through the detour in a sharply curved pathway

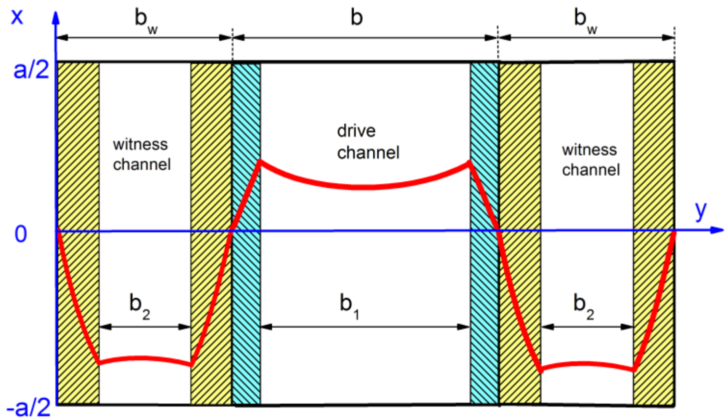
PTI Experiment in AWA

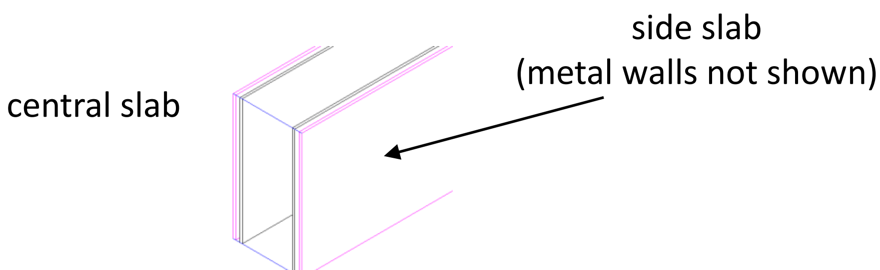
COAXIAL STRUCTURE EMPLOYING ANNULAR DRIVE BUNCH



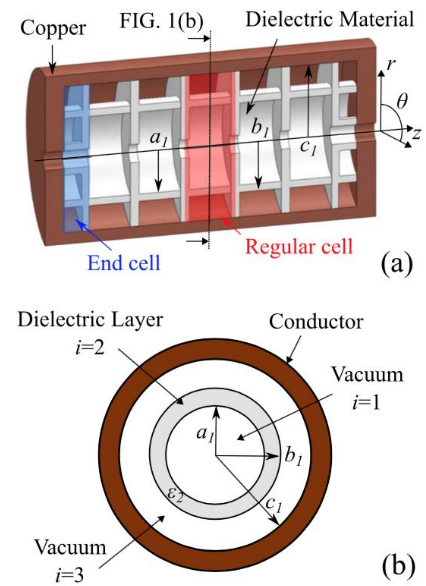
Novel structure designs

DIELECTRIC WAKEFIELD RESONATOR





Dielectric Assist Accelerator (DAA)



Low loss

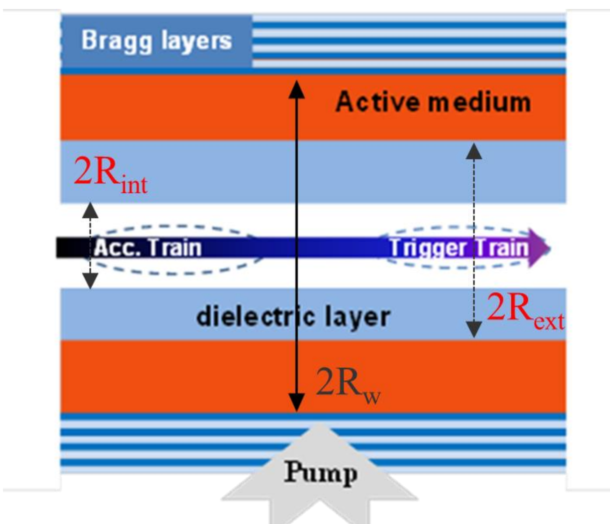
Electromagnetic Wake Amplification by Active Medium - PASER

Particle acceleration through stimulated emission of radiation

Large wake field can be obtained at *large waveguide radius*

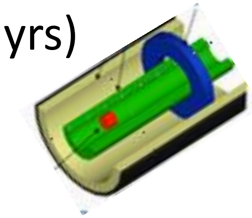
High efficiency acceleration (close to 100%) can be obtained with large energy *spread in the saturation regime*

Modest efficiency (order of 1%) with small energy spread can be obtained *in the saturation and linear regimes*

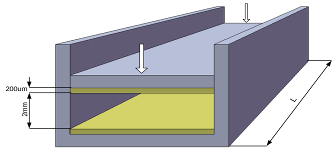


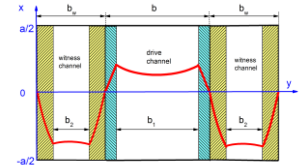
Drive-bunch dynamics (I)

- Longitudinal bunch shaping → improve transformer ratio:
  - **Numerical investigations** + improvements of various shaping methods (5 yrs)
  - **Experimental characterization** + performances of various shaping methods (5 yrs)
  - Couple best performing shaping method to the planar/cylindrical structure (5-10 yrs)
  - Demonstrate enhanced transformer ratio by injecting a shaped bunch in a wakefield structure (5-10 yrs)
- Transverse shaping → match structure
  - Investigate stability of transversely of shaped (annular) beam (5-10 yrs)
  - Beam dynamics (e.g. BBU) of flat beams in structures (5 yrs)
  - Coupling flat beams to Planar structure (5-10 yrs)



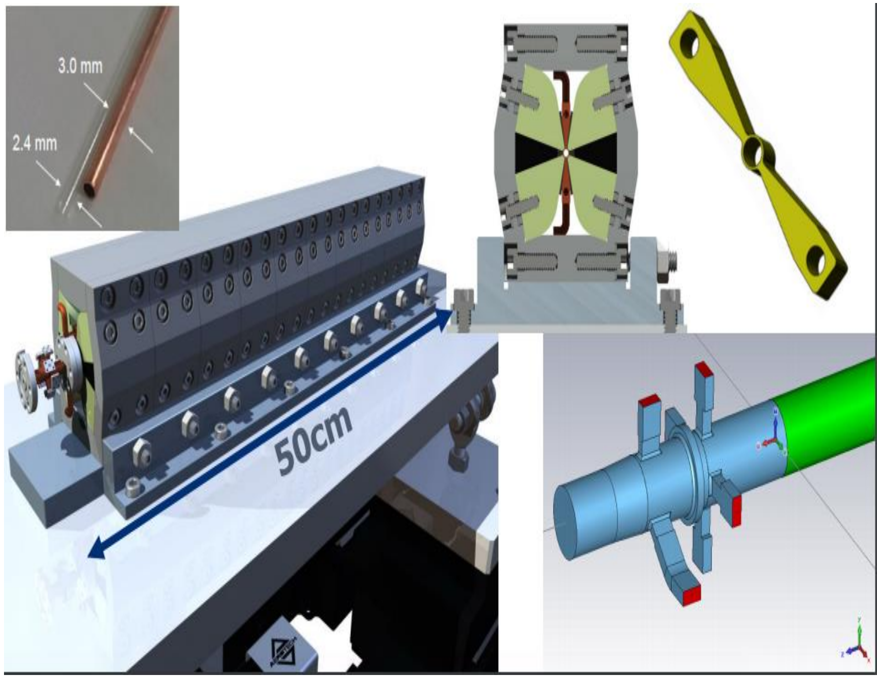
- Combining longitudinal + transverse shaping
  - Optimize longitudinally-shaped beam for a selected structure (5-10 yrs):
    - » Planar structure + flat beam
    - » Coaxial structure + flat beam
    - » 3-channel structure + flat beam





Drive-bunch dynamics (II)

- e- source for drive beam for THz-scale structures:
  - Combine FEL injector design with shaping (5-10-yrs)

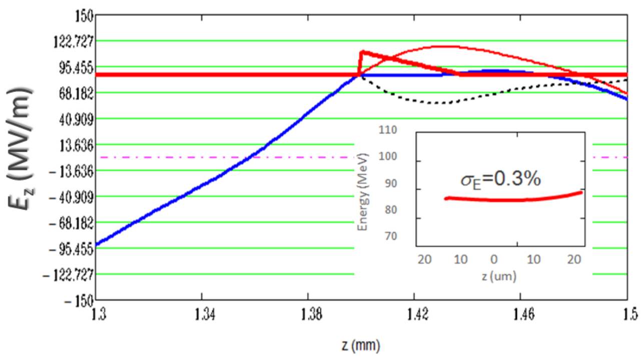


- Experimental investigation of BBU
  - Cylindrical dielectric structures (5 yrs)
  - Planar dielectric & novel structure (5-10 yrs)
  - Investigation with flat beam with longitudinal shaping (5-10 yrs)

Main Beam dynamics

- Longitudinal shaping for improved efficiency
  - Reduce Energy Spread (trapezoidal current distribution)
  - Benefit to CWA and/or TBA (e.g. CLIC)
  - PoP Experimental demonstration (5 year)
  - Simulation for full LC (5 year)

Reverse triangular main bunch



- Transverse dynamics
  - Flat beam needed at IP (cylindrical/planar)
    - Transport and emittance preservation
      - simulation (5 years)
      - experimental demonstration of substantial module (10 years)
  - CWA: Transverse stability
    - Does drive beam instability effect main beam?
    - Simulation (5 year)
    - Experimental tolerances (10 year)

- Sources:
  - e+ source:
    - ideas needed for THz-scale structures (5/10/15 year)
  - e- source:
    - damping ring free option: RF photoinjector-quality beam AND phase space manipulation
    - Simulation (5 year)
    - Experimental demonstration (10 year)

Staging

- TBA/CWA
  - Needs to be demonstrated at THz-scale
  - Arrival Time Jitter will be a key issue at high frequency
    - State of the art rms jitter ~6fsec (or 0.06 degree at 1 THz)
  - CWA Transverse position jitter

Facility & Synergy

Structure Based Wakefield Acceleration

European Facilities and collaboration

Name	CLEAR	CLARA	FlashForward	Sinbad	PITZ	SPARC_LAB	PSI ATHOS beamline	Max IV injector	FLUTE
Country	Switzerland	UK	Germany	Germany	Germany	Italy	Switzerland	Sweden	Germany
Laboratory	CERN	Daresbury	DESY, Hamburg	DESY, Hamburg	DESY, Zeuthen	INFN, Frascati		Max IV	KIT
Type of facility	Advanced Accel, research	Test facility for UKFEL R&D	DESY tests of PWFA	Adv. accel. research	facility	Adv. accel. research		no funding) to create a 3	THz tests
Online when?	Summer 2017	Summer 2017 (50 MeV)	mid-2017	2018 ?	Online	Online		commissioning. Parameters	online (?)
Energy	130-200 MeV (60 with upgrade)	50 MeV (Jan 2017) 250 MeV (Sept 2019)	1.25 GeV	100 MeV	25 MeV	150 MeV	3 GeV	3 GeV	41 MeV
Source type	RF photoinjector	RF photoinjector	RF photonijecotr	RF photoinjector	RF photoinjector	RF photoinjector	RF photpinjector	RF photoinjector	RF photo
Two beam capable		possible							
Shaping capable			yes, two-freq & twin laser-based		laser-shaping on photocathode	uv pulse train			
Energy spread	< 1 MeV FWHM (< 0.2 % rms)	25 to 100 keV rms	0.10%	< 0.3% (low charge, peak	<0.5%	0,1%	0.10%	<0.05% + chirp	
RF Frequency	3 GHz	3 GHz	1.3 GHz and 3.9 GHz	3 GHz	1.3 GHz	2.856 GHz	3 GHz	3 GHz	3 GHz
Rep. rate	1 or 5 Hz (25 Hz with upgrade)	10 Hz	10 Hz	10 - 50 Hz	10 Hz	10 Hz	100 Hz	10 (100) Hz	10 Hz
Time structure	1.5 GHz: 1-40 bunches	single bunch	single or double bunch	single bunch	bunches at 1 MHz rep rate	single bunch or up to 4 bunches at 1 THz rep rate	twin laser based & two-freq shaping & microbunching		single bu
Bunch length	4 ps FWHM (~ 500 um rms)	35 fs to 1.9ps FWHM	10-500fs	sub-fs - 2 fs (low charge)	rise/fall time; 22ps FWHM	30 fs - 5 ps	6 - 25 fs (3kA)	10-500 fs	1 - 300 fs
Charge per bunch	10 pC to 0.5 nC (for < 30 bunche	25 to 250pC	250 pC	0.5 pC - 20 pC for fs bunc	20 pC to 4 nC	0.1-0.8 nC	10-200 pC	20-200 pC	1 - 3000
Normalized	20 um for 0.4 nC	0.5 to 1.0um	2 um	< 0.5 um	0.6 um for 1 nC	1 um	100 -300 nm	< 1um	
More information	Link to info		Link to info	Link to info	.com/referencewor	Link to info			

*Courtesy of Eric Adli + new entries

*Facilities meet the basic requirements for SWFA but need to add some capabilities such as LBS

International Facilities and collaboration

ATF2-Japan	ATF	ATF2-BNL	AWA	FACET-II	ESTB	FAST	CESR-TA	LEA
Japan	USA	USA	USA	USA	USA	USA	USA	
KEK	BNL	BNL	Argonne	SLAC	SLAC	Fermilab	Cornell	
	Adv. accel. research and technology development	Adv. accel. research and technology development	Adv. accel. research	Adv. accel. research	Adv. accel. research	Adv. accel. research	e+/e- damping ring	
Online	Online	~2020	Online	from 2019-2020	Online	Online (50 MeV) Full facility 2019	Online	
1.2 GeV ?	80 MeV	100 MeV (upgradeable)	70 MeV	10 GeV (4.0 - 13.5);	2-15 GeV	300 MeV e- 2.5 Mev p	1.8-5.3 GeV e+/e-	
	RF photoinjector	RF photoinjector						
	No	No					Yes	
	dispersive shaping	dispersive shaping	exchange-based			flat-beam	No	
	0.1%	0.1%	highly variable: 0.1% to 10%	e-: 1.4 % rms (0.4-1.6) / e+: 0.7 % rms (0.5 - 1.5)	0.02%	< 0.2% rms	0.5-1%	
	2.856 GHz	2.856 GHz	1.3 GHz	2.856 GHz		1.3 GHz in SRF, 30 MHz in IOTA	500 MHz	
	1.5 - 6 Hz e-, 0.1 Hz CO2 Laser	1.5 - 6 Hz e-, 0.1 Hz CO2 Laser	10 Hz	e-: 30 Hz (1-30) / e+: 5 Hz (1 - 5)	5 Hz	5 Hz	CW	
	Single bunch, 30 bunch train (25 ns spacing)	Single bunch, 30 bunch train (25 ns spacing)	1.3 GHz variable train: 1-32 bunches	single or double bunch	single or double bunch	3 MHz (1 ms pulse), 9 MHz max.	4ns to 2.6 us	
	1 - 8ps, 100fs w/compressor	1 - 8ps, 100fs w/compressor	highly variable: 300 fs to 10 ps	e-: 1.8 um rms (1.5 - 20) / e+: 16 um rms (16-20)	100 um	4 ps (rms) nominal	30 ps	
	0.1-2 nC	0.1-2 nC	highly variable: 50 pC to 100 nC	e-: 2 nC (0.7 - 5) / e+: 1 nC (0.6 - 2)	350 pC	10 fC to 3.2 nC (for 3000 bunches)	0 - 10nC	

*Courtesy of Eric Adli + new entries

*Facilities meet the basic requirements for SWFA but need to add some capabilities such as LBS

Synergies between linear collider concepts

- **Synergy beam driven PWFA (WG2)**
  - SWFA drive beams can study PWFA at lower (~ 3 GV/m) gradient. (and vice-versa)
  - Explore the beam synchronizations between the drive and witness.
  - Determine the tolerances, confirm the simulation.
  - Enhanced Transformer Ratio studies
- **Synergy with DLA (WG4)**
  - Novel Main Accelerating dielectric structure
  - Determine breakdown limits

SWFA Roadmap