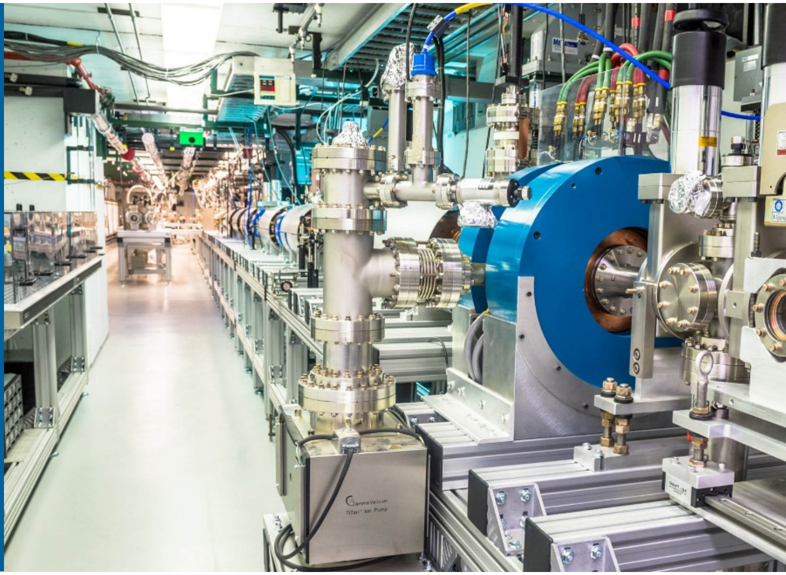
A 500 MeV SHORT-PULSE TBA DEMONSTRATOR AT AWA



JIAHANG SHAO

UCHICAGO ARGONNE LLC
U.S. DEPARTMENT OF ENERGY
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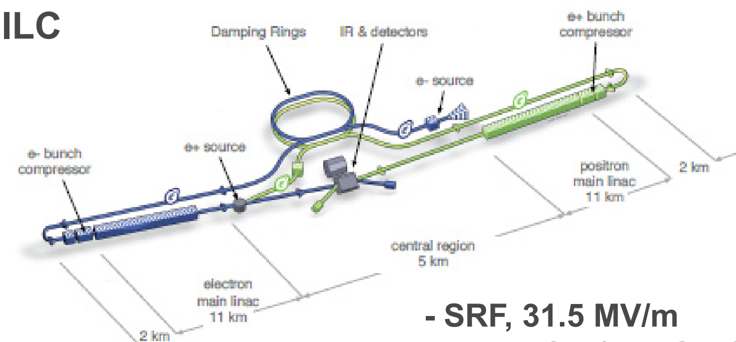
NAPAC2019
North American Particle Accelerator Conference: 1-6 September 2019

BACKGROUND AND MOTIVATION

Future linear colliders

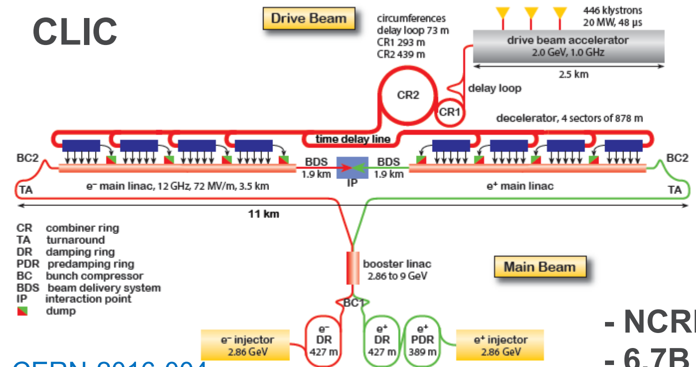
ILC



- SRF, 31.5 MV/m
- 7.8B USD (500 GeV)

ILC TDR

CLIC

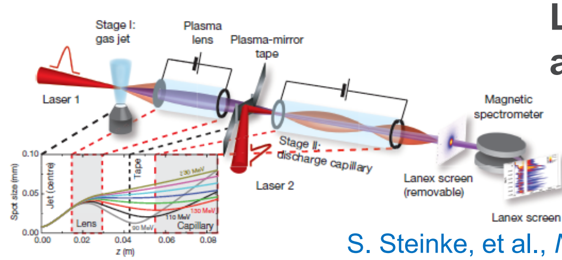


- NCRF, 72 MV/m
- 6.7B CHF (380 GeV)

CERN-2016-004

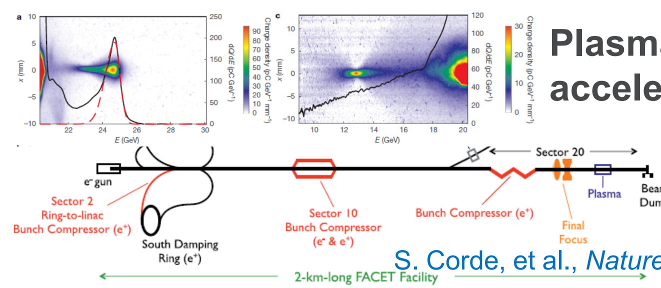
Advanced accelerator concepts

Laser wakefield acceleration



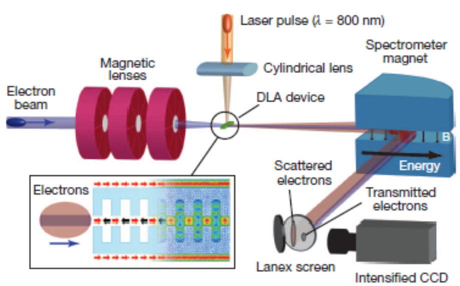
S. Steinke, et al., *Nature* **530**, 190 (2016)

Plasma wakefield acceleration



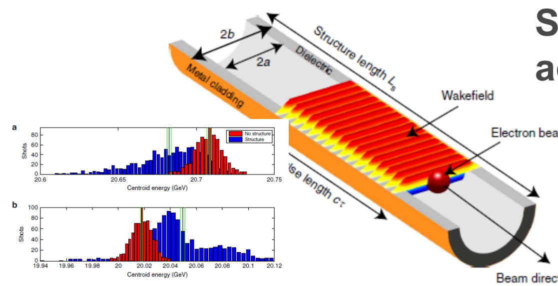
S. Corde, et al., *Nature* **524**, 442 (2015)

Dielectric laser acceleration



E.A. Peralta, et al., *Nature* **503**, 92 (2013)

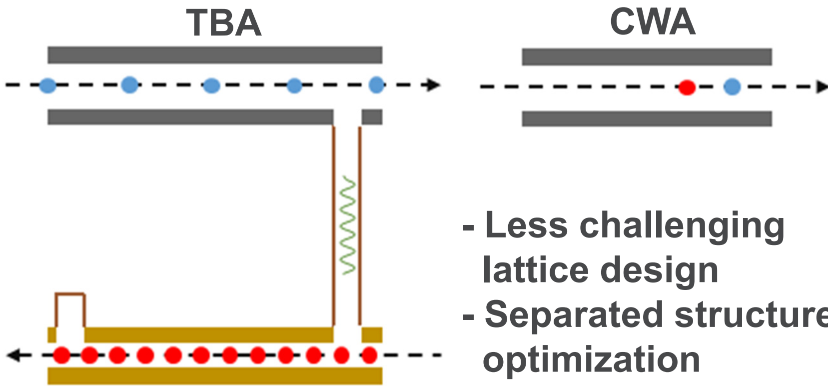
Structure wakefield acceleration



B.D. O'Shea, et al., *Nature Comm.* **7**, 12763 (2016)

BACKGROUND AND MOTIVATION

Two-beam acceleration (TBA)

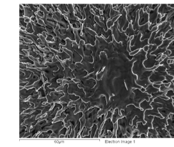


- Less challenging lattice design
- Separated structure optimization

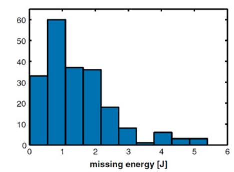
Short pulse

$$BDR \propto E^{30}\tau^{5}$$

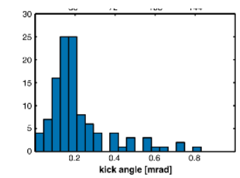
- Structure damage



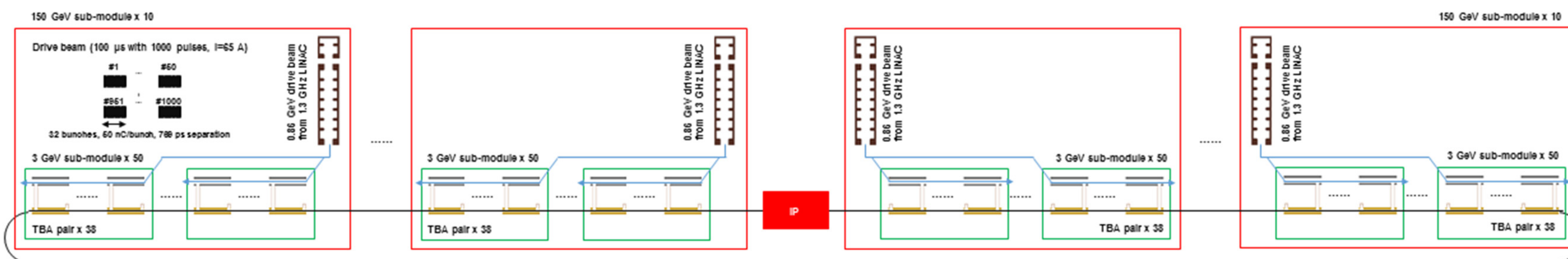
breakdown



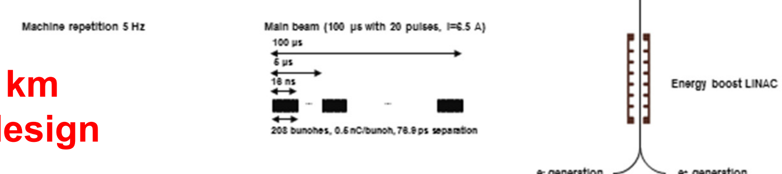
- Beam loss
- Energy reduction



Argonne Flexible Linear Collider (AFLC)



3 TeV, 18 km
Module design



- **26 GHz** structure
- **22 ns** short pulse
- **1 GW** rf power
- **267 MV/m** gradient

W. Gai, et al., *JPP* **78**, 339 (2012)

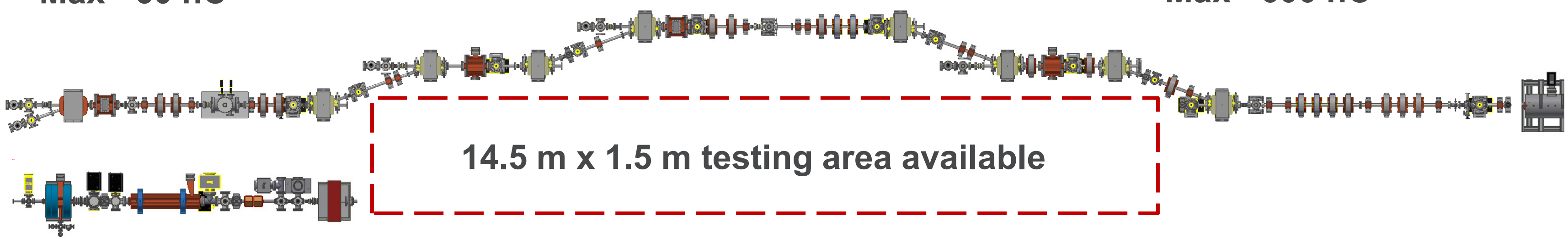
T. Inagaki, et al., *PRSTAB* **17**, 080702 (2014)
W. Wuensch, Proceedings of EPAC2002
A. Palaia, et al., *PRSTAB* **16**, 081004 (2013)
A. Grudiev, et al., *PRSTAB* **12**, 102001 (2009)

BACKGROUND AND MOTIVATION

Argonne Wakefield Accelerator facility (AWA)

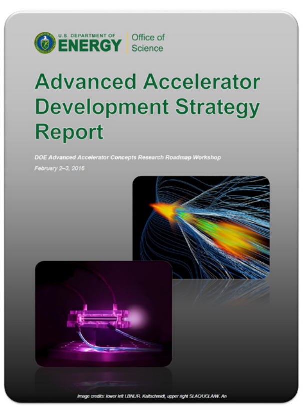
15 MeV main beam
Single bunch
Max ~60 nC →

← 70 MeV drive beam
1.3 GHz bunch train
Max ~600 nC



- Two independence beamlines
- World's highest charge drive beam
- Flexible beamline configuration
- Beam shaping by DEEX
- Start-to-end structure development
- Separated high power test-stands

Short-pulse TBA R&D at AWA



- Drive beam power source

300 MW → 1 GW

- Main beam acceleration

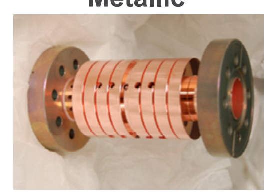
150 MeV/m → 267 MeV/m

- Staging acceleration to high energy

Multi-stage | Multi-structure | High fidelity

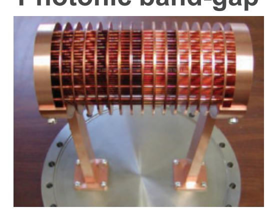
5 MeV → > 100 MeV

Metallic

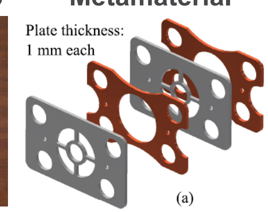


Dielectric

Photonic band-gap



Metamaterial



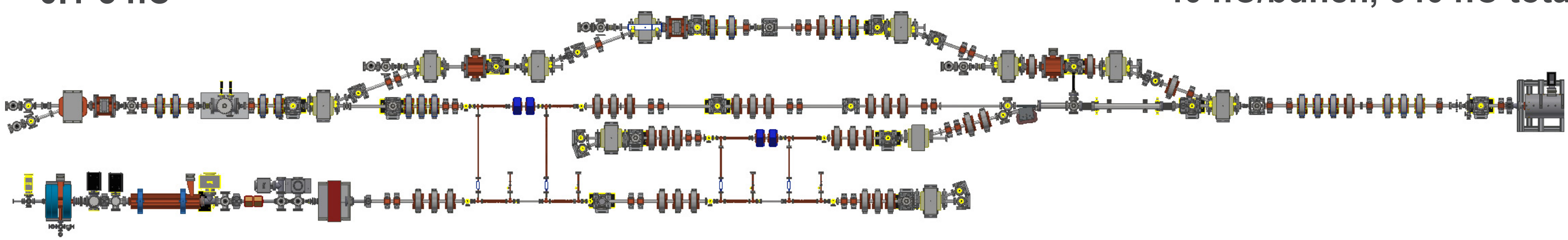
C. Jing, et al, *NIMA* **898**, 72 (2018)
J. Shao, et al, arXiv 1907.01069 (2019)
E. Simakov, et al., *PRL* **116**, 064801 (2016)
X. Lu, et al., *PRL* **122**, 024801 (2019)

CONCEPTUAL DESIGN OF THE HIGH ENERGY DEMONSTRACTOR AT AWA

Proposed layout

15 MeV main beam
Single bunch
0.1-3 nC →

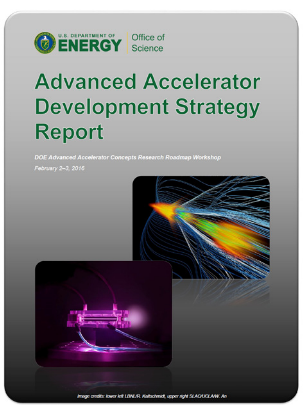
← 70 MeV drive beam
2 x 8-bunch trains
40 nC/bunch, 640 nC total



- 2 stages
- 2 pairs of structures per stage

- Drive beam: 70 to ~20 MeV
- Main beam: 15 to ~500 MeV

Short-pulse TBA R&D at AWA



- Drive beam power source

1 GW | >>1 GW

- Main beam acceleration

267 MeV/m | GeV/m

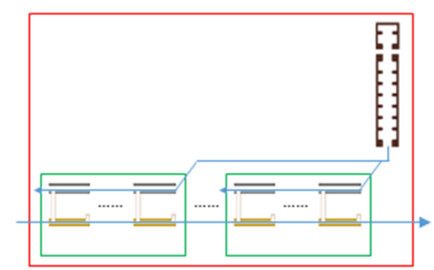
- Staging acceleration to high energy

Multi-stage | Multi-structure | High fidelity

> 100 MeV | >GeV

High current bunch train acceleration

Milestone of short-pulse TBA based linear collider



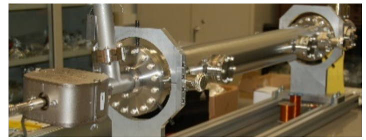
500 MEV SHORT-PULSE TBA DEMONSTRATOR

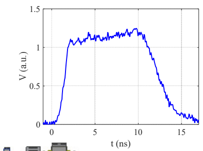
- Timing control for staging acceleration
- Structure optimization consideration for the maximum energy gain
- Preliminary structure design results

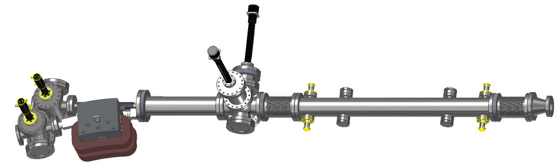
STAGING ACCELERATION

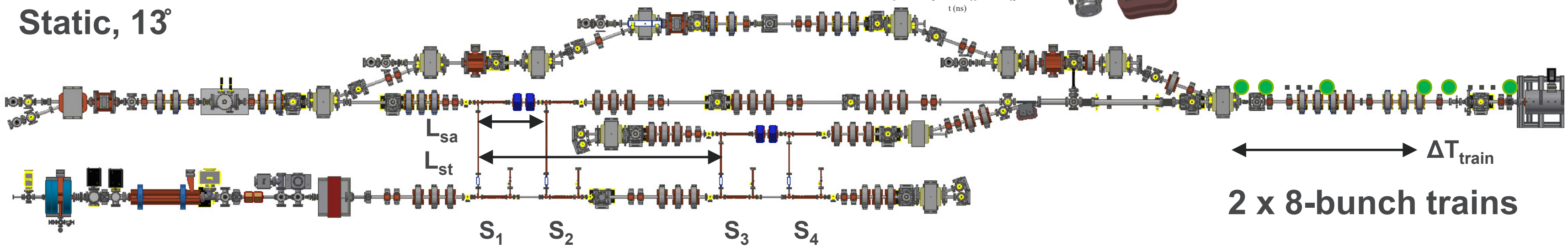
Drive beam distribution

- Fast kicker:
  30 kV, 2 ns rising, 2°
- Septum
  Static, 13°



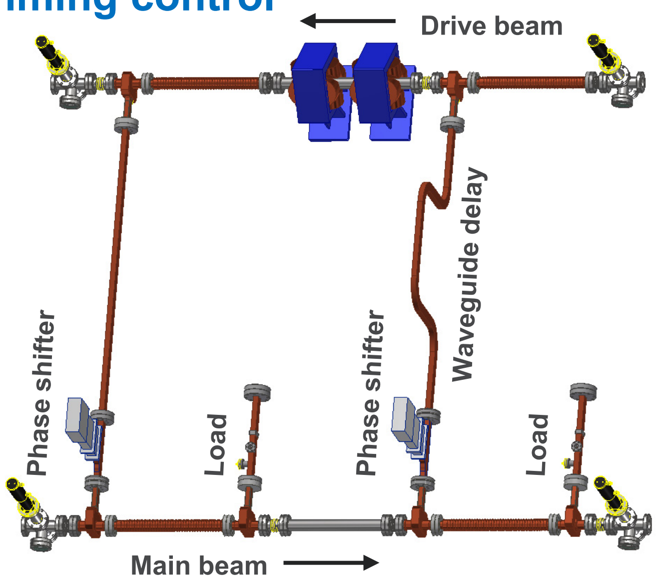






2 x 8-bunch trains

Timing control



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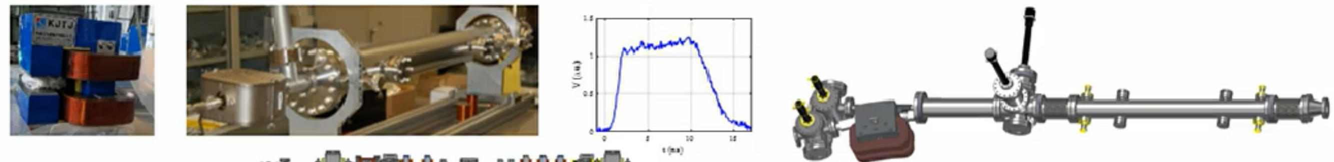
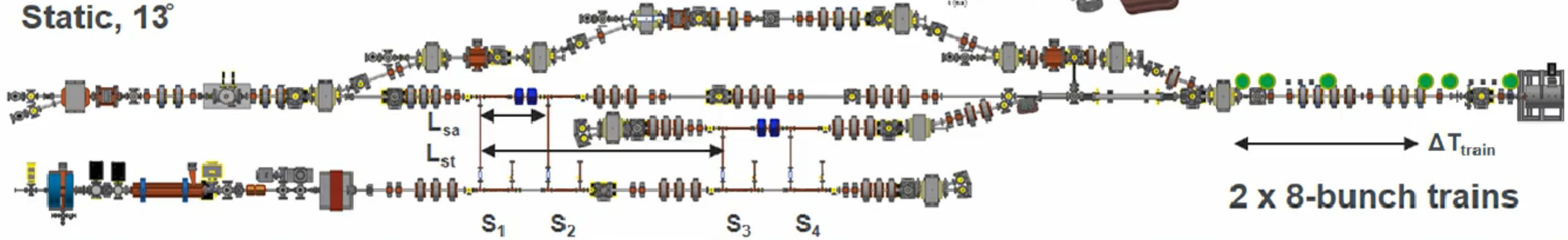
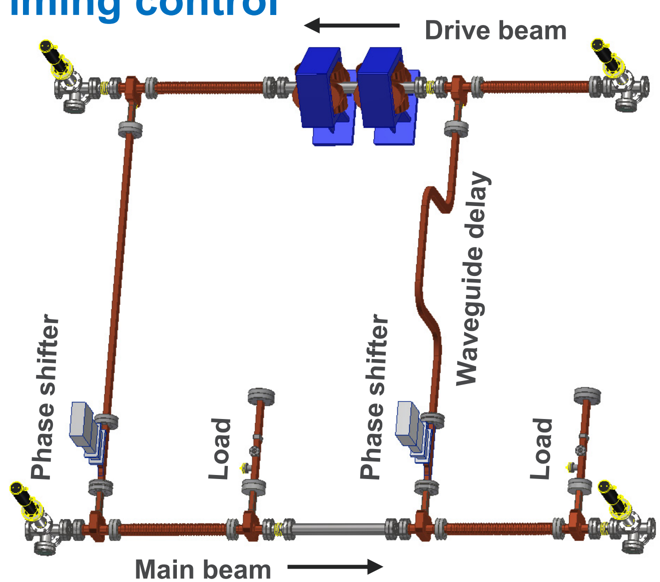




Timing control



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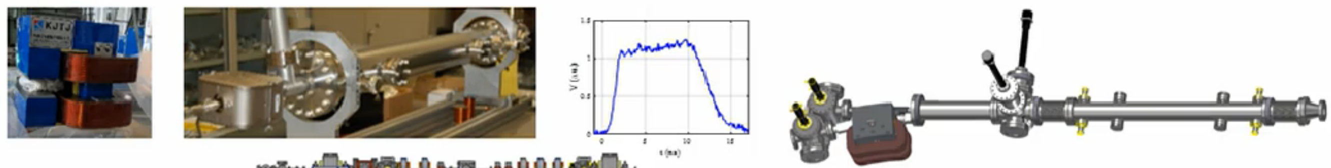
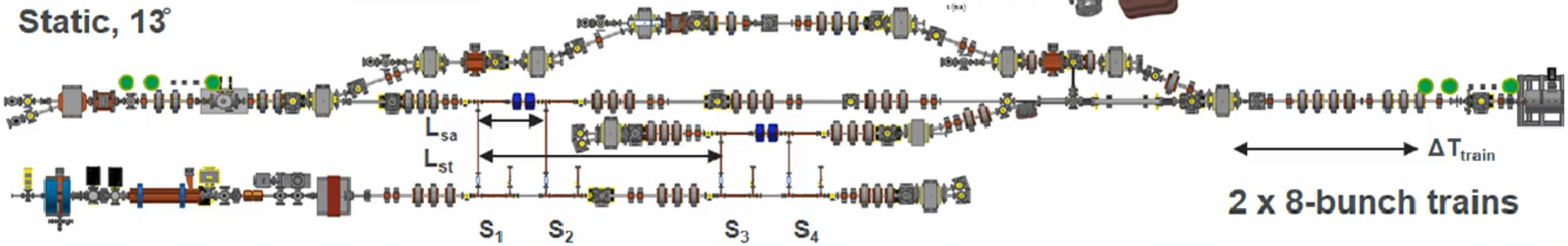
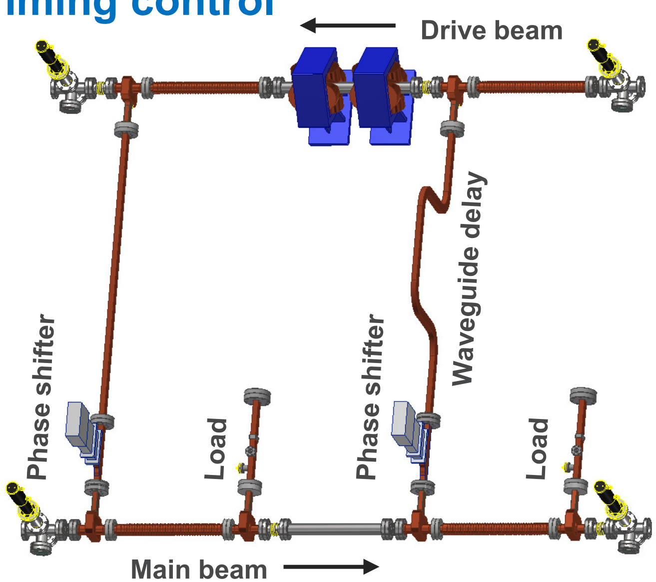




Timing control



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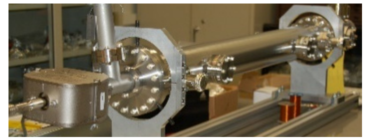
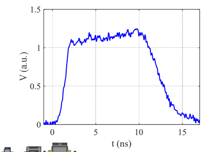
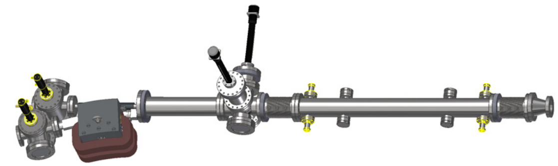
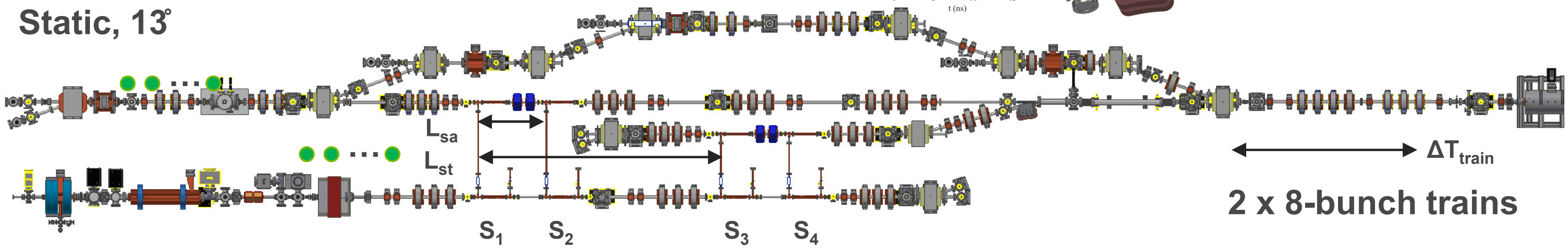
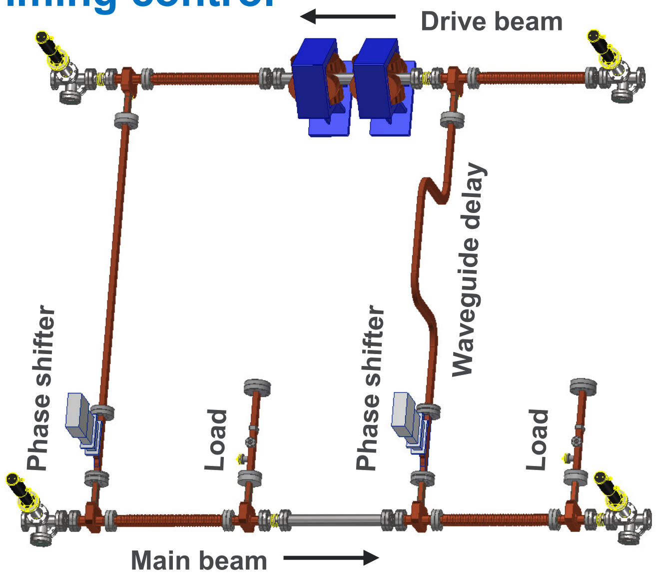








Timing control



Arrival time at each structure				
Main	S_1	S_2	S_3	S_4
	T_m	T_m+L_{sa}/c	T_m+L_{st}/c	$T_m+(L_{sa}+L_{st})/c$
rf	S_1	S_2	S_3	S_4
	$(L_{sa}+L_{st})/c$	$L_{st}/c+\Delta T_{delay}$	$\Delta T_{train}+L_{sa}/c$	$\Delta T_{train}+\Delta T_{delay}$

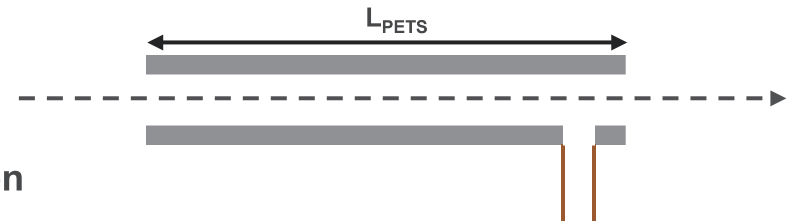
$\Delta t_{train}=2L_{st}/c$ >10 ns; $\Delta t_{delay}=2L_{sa}/c$ -> waveguide length ~ several meter

- Train separation determined by the stage length
- Waveguide delay determined by the structure length
- Fine timing adjusted by the phase shifters

STRUCTURE OPTIMIZATION CONSIDERATION

Power extraction

- rf generation via Cherenkov radiation
- Wakefield superposition in bunch train



*Ignore structure attenuation

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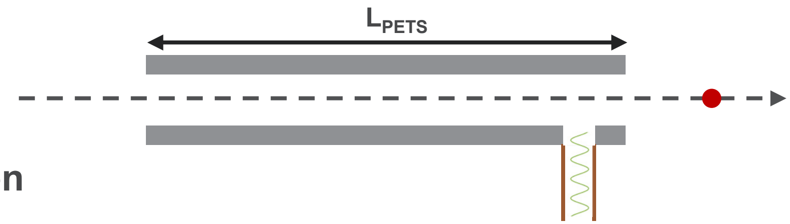

- Wakefield superposition in bunch train

*Ignore structure attenuation

$$P_1 = \frac{c\beta_{g,PETS}\kappa_{L,PETS}}{1-\beta_{g,PETS}} Q_b^2 F^2$$

STRUCTURE OPTIMIZATION CONSIDERATION

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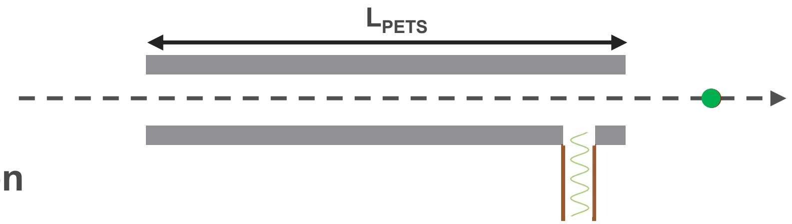

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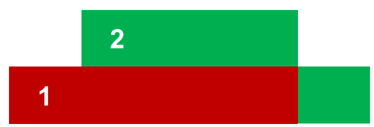

*Ignore structure attenuation

P_1

$$P_1 = \frac{c\beta_{g,PETS}\kappa_{L,PETS}}{1-\beta_{g,PETS}} Q_b^2 F^2$$

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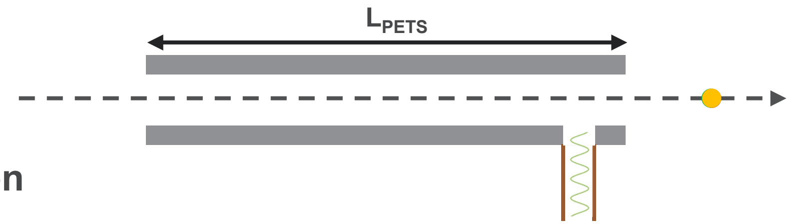

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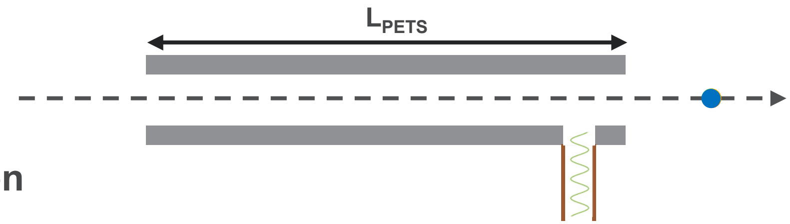
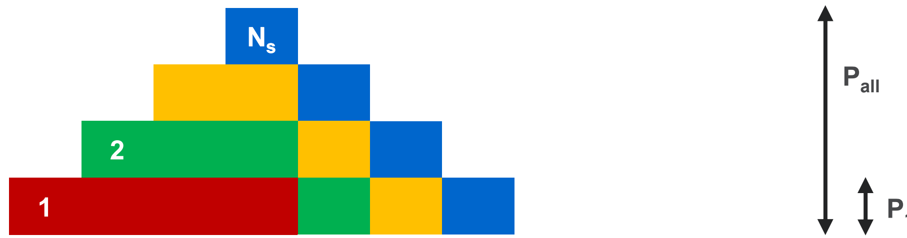


- Wakefield superposition in bunch train



$$P_{all} = P_1 N_s^2$$

$$P_1 = \frac{c\beta_{g,PETS}\kappa_{L,PETS}}{1-\beta_{g,PETS}} Q_b^2 F^2$$

*Ignore structure attenuation

STRUCTURE OPTIMIZATION CONSIDERATION

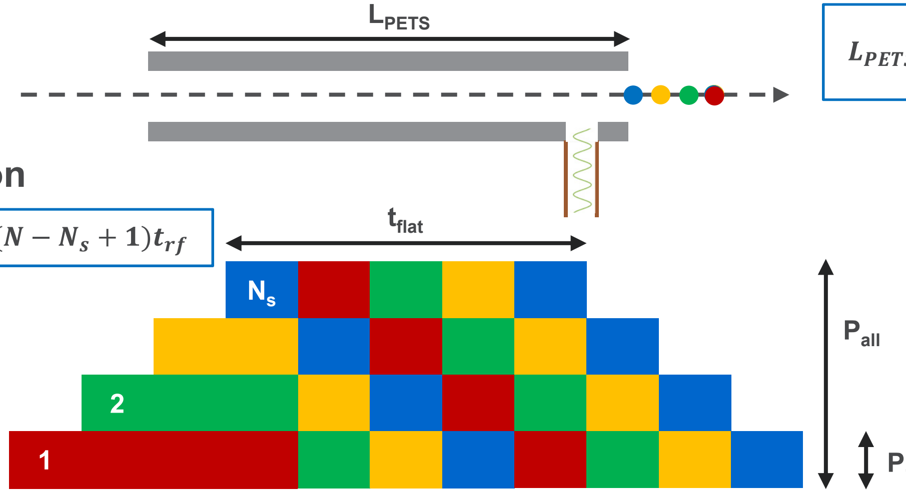
Power extraction

- rf generation via Cherenkov radiation

- Wakefield superposition in bunch train

$$L_{PETS} = \frac{c\beta_{g,PETS} t_{rf}}{1-\beta_{g,PETS}} N_s$$

$$t_{flat} = (N - N_s + 1)t_{rf}$$



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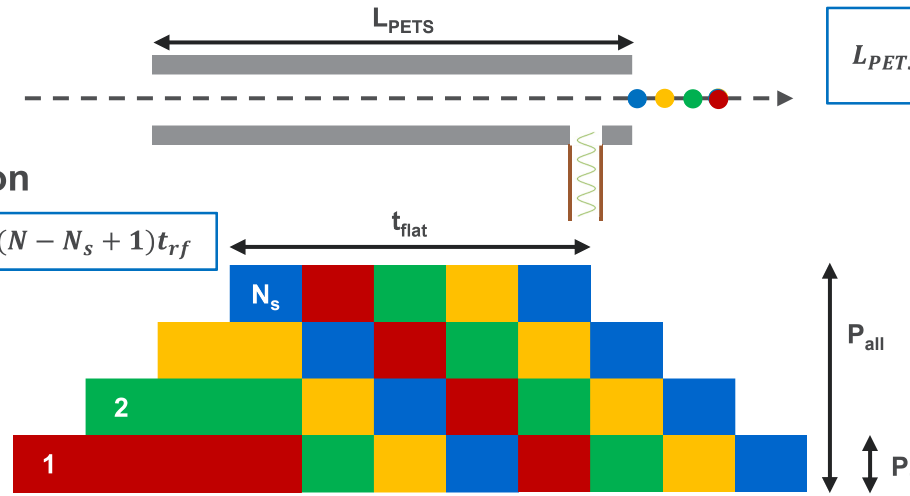

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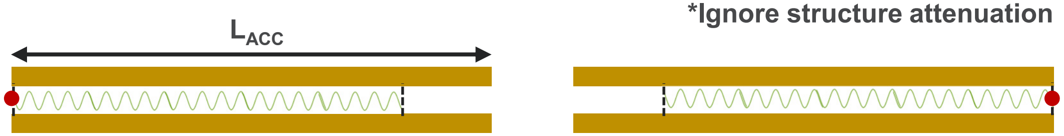
*Ignore structure attenuation

Acceleration

*Ignore structure attenuation



- Minimal structure length for full acceleration

$$L_{ACC} = \frac{c\beta_{g,ACC}}{1 - \beta_{g,ACC}} t_{flat} = (N - N_s + 1)t_{rf}$$

- N_s set to 4
- $t_{flat} = 3.8\ ns$

- Accelerating gradient

$$E_{ACC} = \sqrt{\frac{P_{in}\omega r_{ACC}}{\beta_{g,ACC} c Q_{ACC}}} \propto N_s$$

- Maximum energy gain

$$W = E_{ACC} L_{ACC} \propto (N - N_s + 1)N_s$$

Beam transmission

$$L_s \leq \frac{\beta\gamma a^2}{k^2 \varepsilon_n}$$

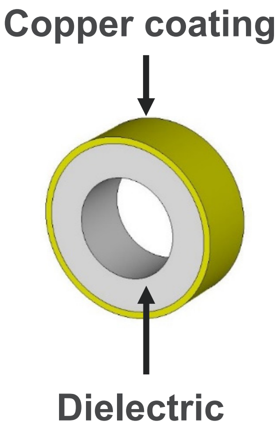
- k set to 3 for >99% transmission
- $\beta\gamma$ set to the lowest energy

Available space

- $L_s \leq 0.5\ m$

STRUCTURE OPTIMIZATION

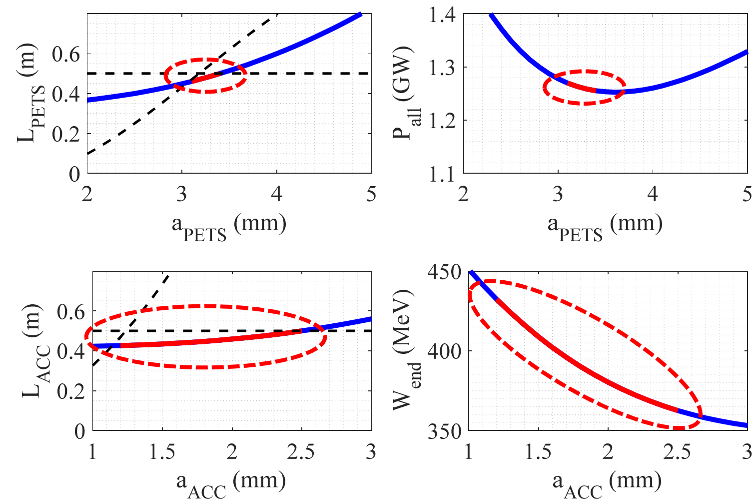
Dielectric loaded structure



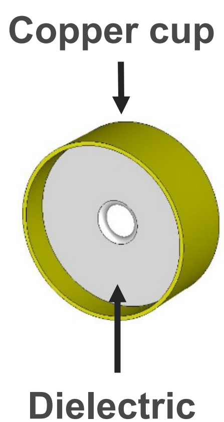
- Low surface field
- Low fabrication cost
- Most developed dielectric structure

- Moderate shunt impedance

- Adjustable parameters: a, ε_r



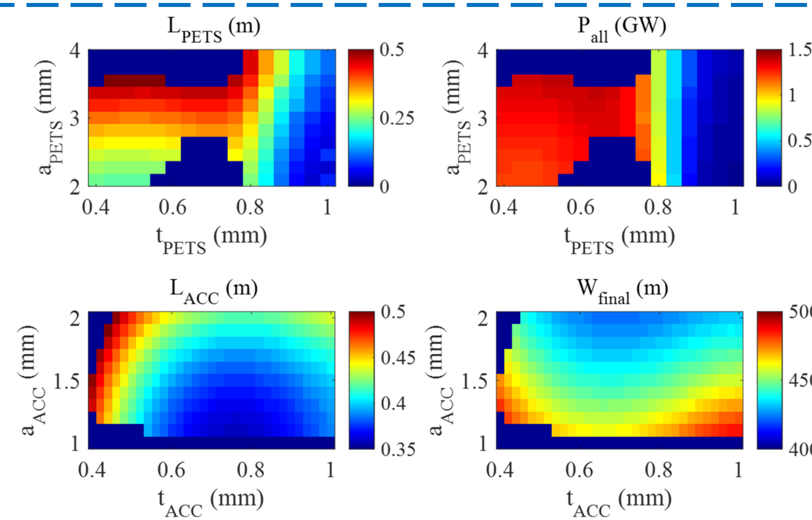
Dielectric disk structure



- High shunt impedance
- Easy to tune
- Can be applied to build long structure

- High surface field at iris
- Structure under development

- Adjustable parameters: a, ε_r, t, working mode



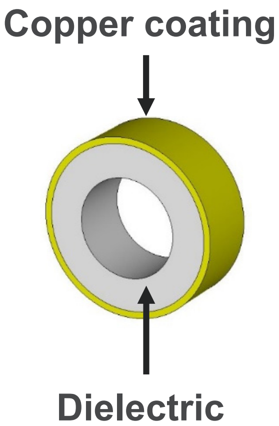
C. Jing, et al., Proceedings of AAC2018

STRUCTURE RESULTS

conservative
- 40 nC drive beam: $\varepsilon_n = 80\ \mu m$
- 0.1-3 nC main beam: $\varepsilon_n = 10\ \mu m$

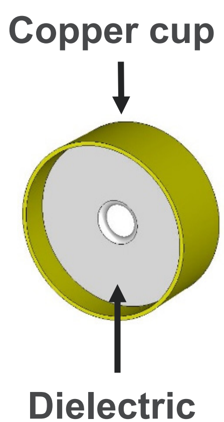
ideal
- 40 nC drive beam: $\varepsilon_n = 40\ \mu m$
- 0.1-3 nC main beam: $\varepsilon_n = 3\ \mu m$

Dielectric loaded structure



	f GHz	ε_r	a mm	r/Q kΩ/m	β_g	L m	P_{flat} GW	$W_{loss,2}$ MeV	$W_{gain,4}$ MeV	G MV/m
PETS	11.7	3.75	1.9	13.9	0.27	0.34	0.83	32.6	/	/
ACC		3.75	1.2	16.4	0.27	0.42	/	/	183	109
PETS	19.5	3.75	2.5	14.4	0.28	0.36	1.19	48.0	/	/
ACC		3.75	1.2	22.7	0.27	0.42	/	/	330	196
PETS	26.0	3.75	3.1	11.6	0.33	0.46	1.27	52.0	/	/
ACC		3.75	1.2	26.1	0.27	0.43	/	/	417	242
PETS	26.0	3.75	2.4	15.4	0.30	0.39	1.37	55.8	/	/
ACC		3.75	0.7	35.3	0.27	0.42	/	/	502	299

Dielectric disk structure



2π/3	f GHz	ε_r	a mm	r/Q kΩ/m	β_g	L m	P_{flat} GW	$W_{loss,2}$ MeV	$W_{gain,4}$ MeV	G MV/m
PETS	11.7	9.8	2.5	10.7	0.33	0.46	0.98	38.0	/	/
ACC		9.8	1.5	14.2	0.30	0.49	/	/	209	107
PETS	19.5	16	3	15.1	0.28	0.36	1.30	50.8	/	/
ACC		9.8	1.5	20.9	0.30	0.49	/	/	374	191
PETS	26.0	38	3.2	13.3	0.31	0.42	1.37	54.2	/	/
ACC		9.8	1.2	28.1	0.30	0.49	/	/	502	256
PETS	26.0	38	2.0	24.5	0.22	0.26	1.37	54.0	/	/
ACC		9.8	0.7	33.6	0.30	0.49	/	/	553	282

C. Jing, et al., Proceedings of AAC2018

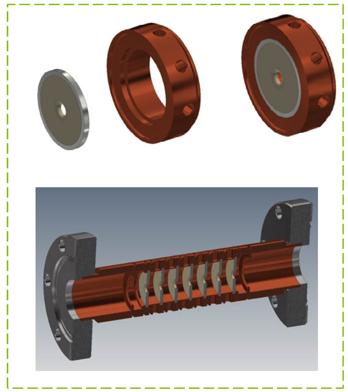
FUTURE STUDY

Structure R&D

- Dielectric loaded structure
  1. Transverse wakefield damping
  2. Matching section design

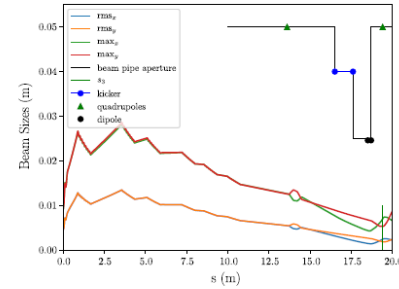
- Dielectric disk structure
  1. Prototype test
  2. Transverse wakefield damping

- rf components



Beamline

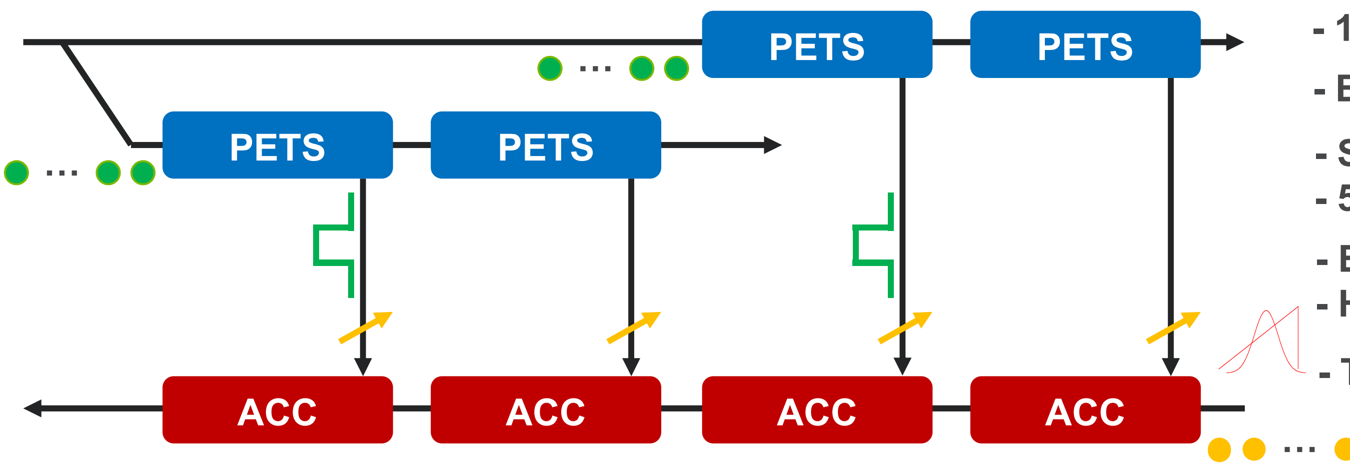
- Start-to-end simulation and optimization of the staging beamline



N. Neveu, et al, *PRAB* **22**, 054602 (2019)

- Kicker and septum beam test

Steps towards the 500 MeV demonstrator at AWA and beyond



- GW output power
- 100 MeV acceleration
- Beam transmission
- Staging
- 500 MeV demonstrator
- Beam shaping
- High beam loading
- Train acceleration

SUMMARY

- **A high energy short-pulse TBA demonstrator is proposed to test critical technology elements for future linear collider**
- **2 stages with 2 structures per stage can physically fit into AWA's current bunker**
- **GW level output power and 200-500 MeV acceleration are promising goals with structure optimization**
- **The structure choice is open and AWA welcomes collaborators to test novel structures**

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THANKS!