IPAC'18, APR 29 – MAY 4, 2018, VANCOUVER, CANADA

Argonne NATIONAL LABORATORY

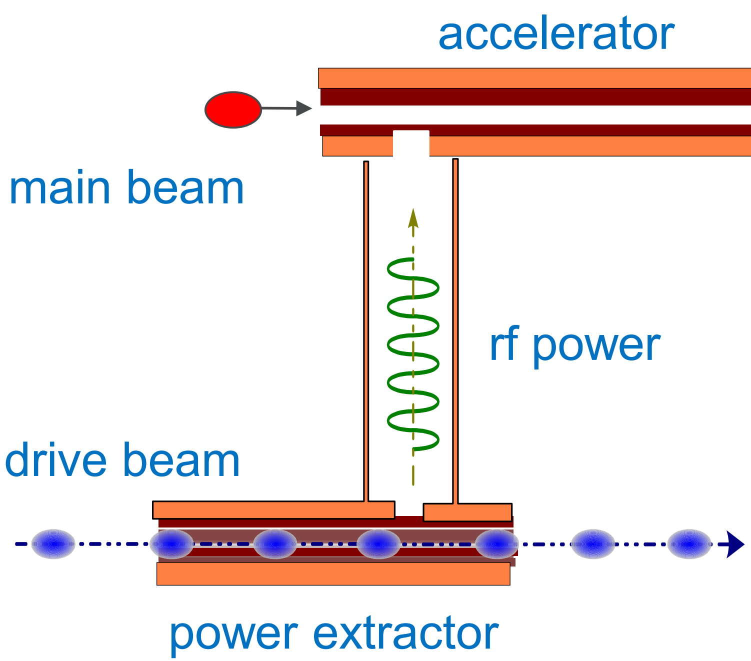
RECENT PROGRESS OF SHORT PULSE DIELECTRIC TWO-BEAM ACCELERATION

JIAHANG SHAO

On behalf of the Argonne Wakefield Accelerator (AWA) facility

BACKGROUND AND MOTIVATION

- **Short pulse two-beam acceleration**
  - Approach to structure-based wakefield acceleration
  - High gradient acceleration (200-300 MV/m) A promising solution!



$$E_0 = \sqrt{2\alpha Z_{eff} P_{in}} \rightarrow \sim\text{GW}$$

TBA

$$BDR \propto E^{30}\tau^5 \rightarrow \sim 20\text{ ns}$$

short pulse

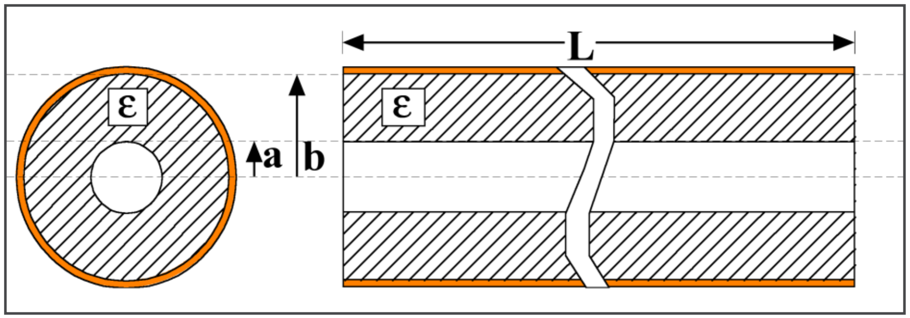
  - Both structures can be optimized to obtain high power generation, high gradient acceleration, and high efficiency

W. Gai, *et al, J. Plasma Phys.*, vol. 78, 339-345, 2012

BACKGROUND AND MOTIVATION

- **Dielectric structure**

  - Slow-wave structure with simple geometry



uniform section

tapered section

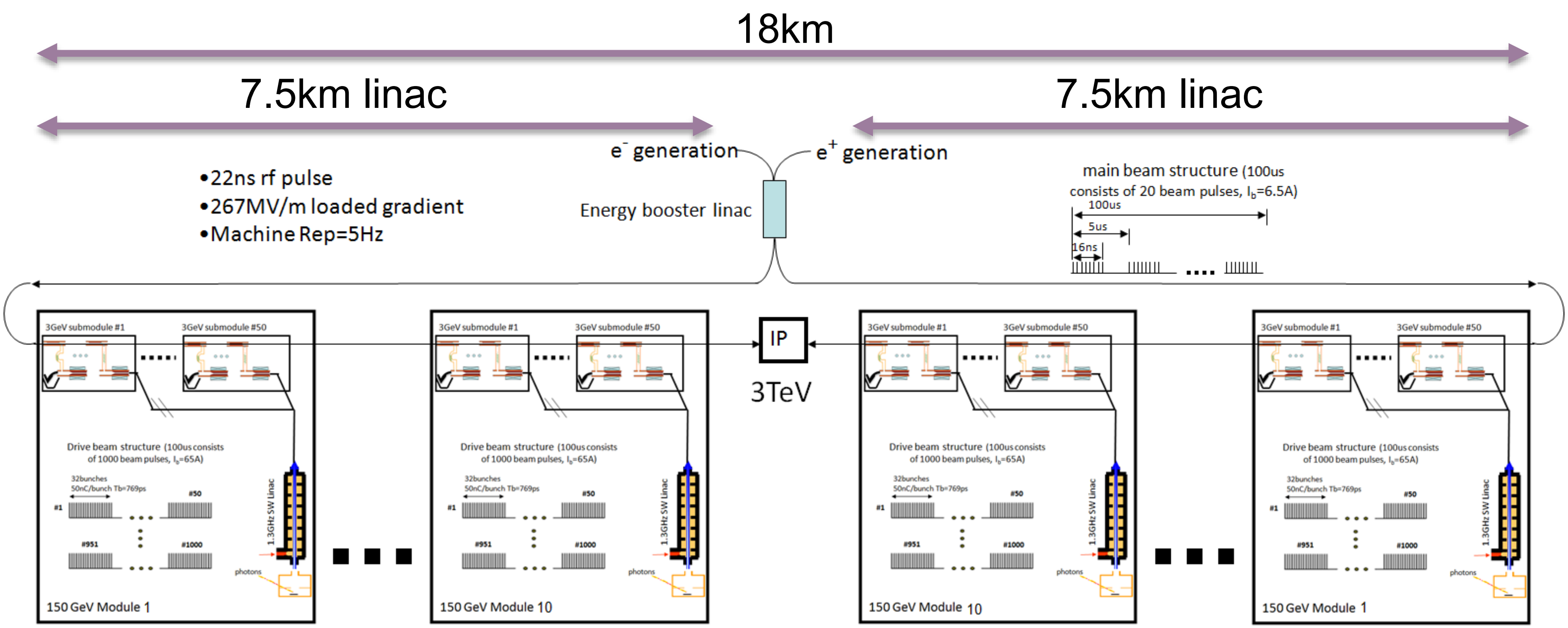
- **Advantages**

  - Simple geometry
  - Small transverse size → low cost
  - No surface electric field enhancement
  - High group velocity: short pulse preferred → high gradient

W. Gai, *et al, J. Plasma Phys.*, vol. 78, 339-345, 2012
B. D. O'Shea, *et al.*, *Nat. Commun.*, vol. 7, 12763, 2016.

BACKGROUND AND MOTIVATION

- **Argonne Flexible Linear Collider (AFLC)**
  - A 3 TeV 30 MW machine based on short-pulse dielectric TBA



- **Uniqueness**
  - High frequency (26 GHz), short rf pulse (~20 ns), high gradient (267 MV/m)
  - Modular design for flexible energy upgrade

W. Gai, *et al*, *J. Plasma Phys.*, vol. 78, 339-345, 2012

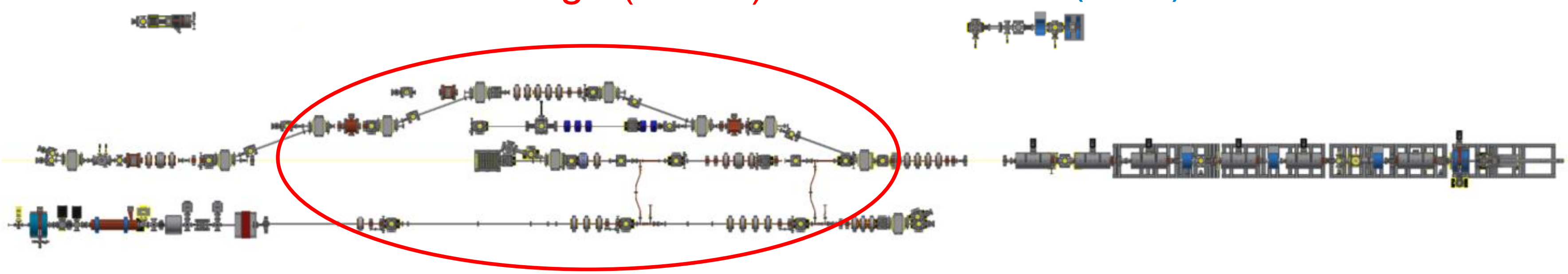
BACKGROUND AND MOTIVATION

- **Argonne Wakefield Accelerator (AWA) facility**
  - A flexible, state-of-art testbed for future linear colliders

breakdown test-stand

Double emittance exchange (DEEX)

Argonne cathode test-stand (ACT)



wakefield experimental area

witness beam

- 15 MeV, single bunch
- 0.05-60 nC

drive beam

- 70 MeV, up to 32 bunches
- Max charge: 100 nC (single)
  600 nC (train)

BACKGROUND AND MOTIVATION

- **Argonne Wakefield Accelerator (AWA) facility**
  - Strong capability in research related to wakefield acceleration
  - **Over 15** collaborators and users

drive → Collinear

D. Wang, et al., PRL 2016
E. Simakov, et al., PRL 2016
H. Zha, et al., PRAB 2016

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drive	→	Collinear
drive+witness	→	TBA

C. Jing, et al., to be published

BACKGROUND AND MOTIVATION

Argonne NATIONAL LABORATORY

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drive	→	Collinear
drive+witness	→	TBA
drive+EEX	→	Bunch shaping Collinear

Q. Gao, et al., PRL 2018
G.Ha, et al.,PRL 2017
A. Halavanau, et al., PRAB 2017
G.Ha, et al.,PRAB 2016

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drive+EEX	→	Bunch shaping Collinear
drive+EEX	→	Plasma Wakefield

Under investigation

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Under investigation

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drive	→	Collinear
drive+witness	→	TBA
drive+EEX	→	Bunch shaping Collinear
drive+EEX	→	Plasma Wakefield
drive+EEX+witness	→	Bunch shaping TBA
ACT	→	Cathode, rf breakdown

J. Shao, et al., PRL 2016
J. Shao, et al., PRL 2015
S. Baryshev, et al., APL 2014

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drive	→	Collinear
drive+witness	→	TBA
drive+EEX	→	Bunch shaping Collinear
drive+EEX	→	Plasma Wakefield
drive+EEX+witness	→	Bunch shaping TBA
ACT	→	Cathode, rf breakdown

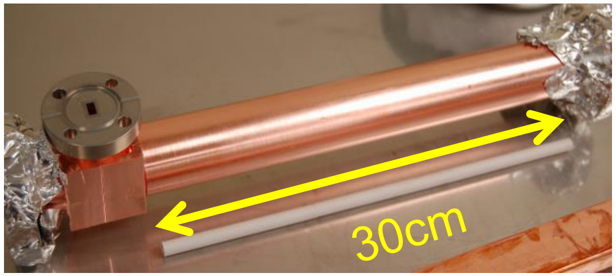
- **Wakefield R&D**
  - Successful tests with metallic structures: **300 MW + 150 MeV/m** for single stage, **70 MeV/m** for two stages
  - Continuous effort in developing dielectric structures

C. Jing, *et al, To be published*

SHORT PULSE DIELECTRIC TBA IN K-BAND -- A PROTOTYPE IN AFLC

STRUCTURE OVERVIEW

- **Prototypes for the basic TBA pair in AFLC**



power extractor

accelerator

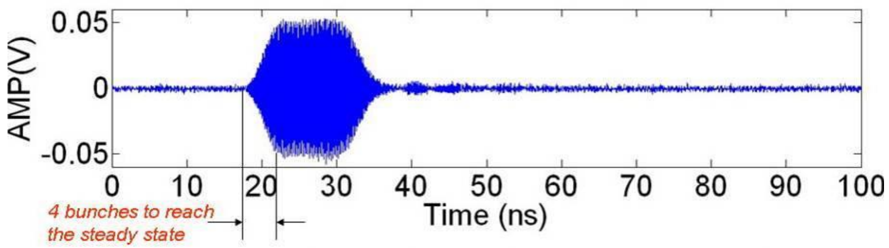
	POWER EXTRACTROR	ACCELERATOR
Frequency (GHz)	26 (20 x 1.3)	26 (20 x 1.3)
ID / OD (mm)	7 / 9.068	3 / 5.026
Dielectric constant	6.64 (Frosterite)	9.8 (Alumina)
Cu coating	No	Yes, 100 μm
Group velocity	0.25 c	0.1115 c
r/Q (Ω/m)	9788	21983
Q	2950	2295
r (MΩ/m)	28.9	50.5

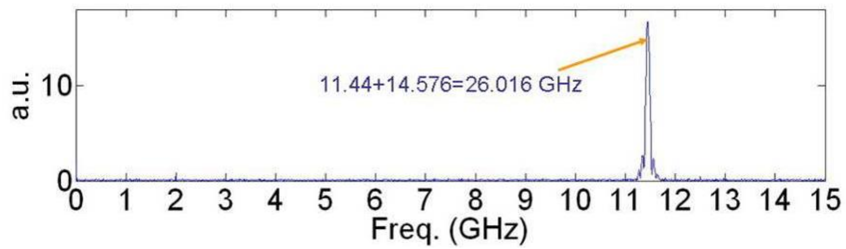
J. Shao, *et al.*, in *Proc. IPAC'2017*, 3305-3307, 2017

HIGH POWER GENERATION

- **2009: low charge**

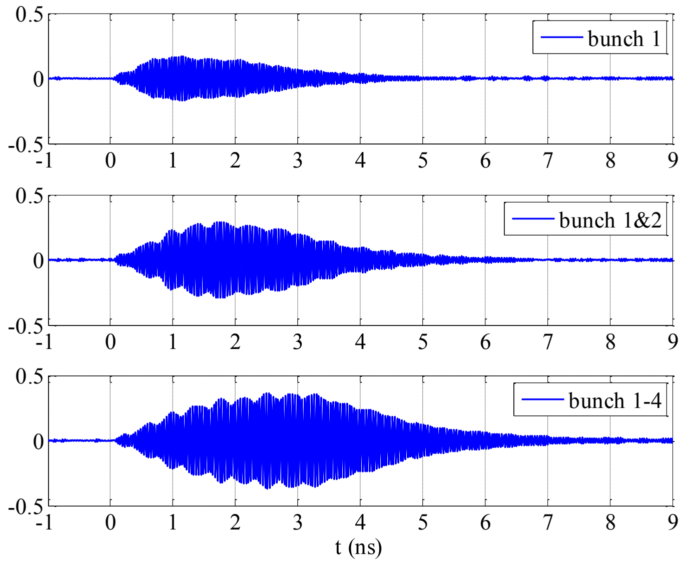
 - Low charge 16-bunch train, 2 MW generated power

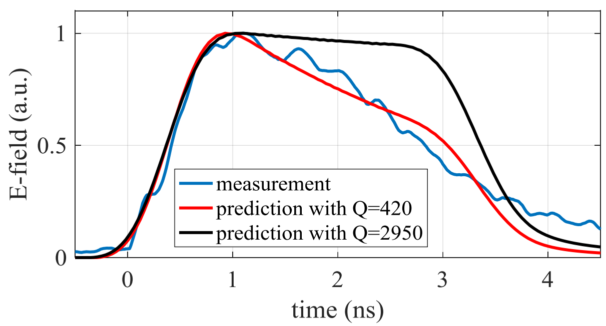




- **2016-2017: high charge**

 - High charge 4-bunch train, **55 MW** generated power



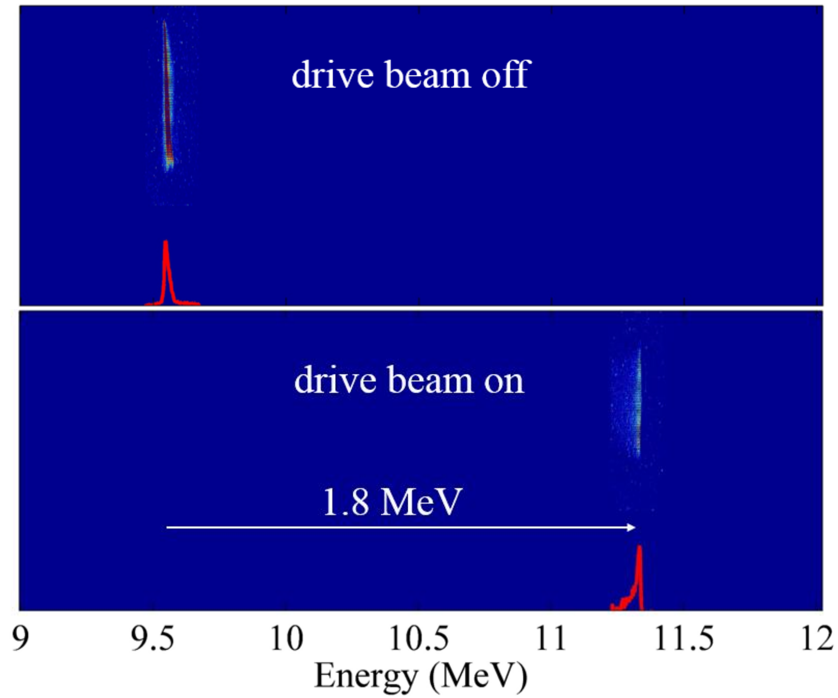


Higher attenuation and surface damage
Mechanism under investigation

MAIN BEAM ACCELERATION

- **Successful demonstration of short pulse dielectric TBA**

  - **1.8 MeV** acceleration, **28 MeV/m** average gradient



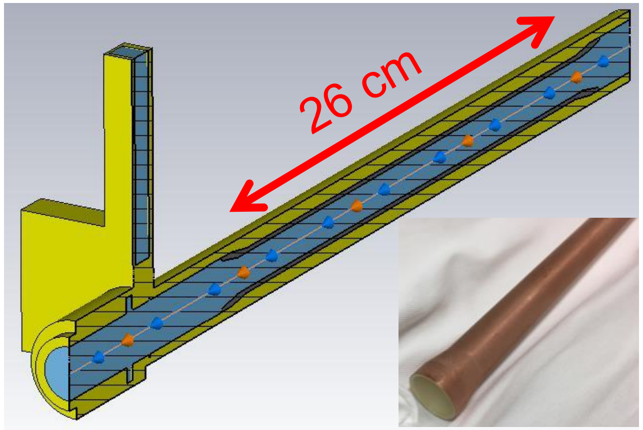
- **Structure inspection**

  - No structure damage was observed after the high power test

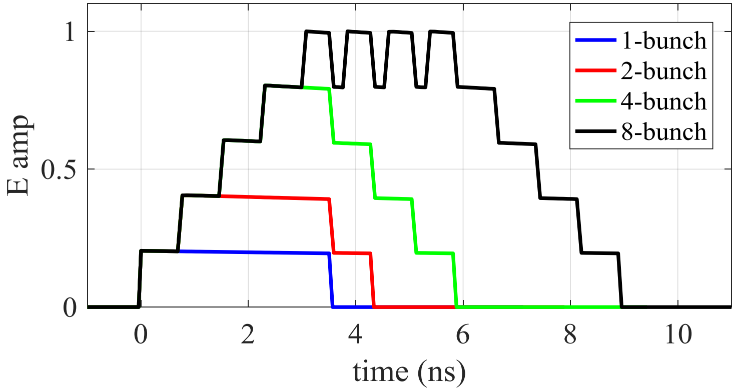
SHORT PULSE HIGH POWER GENERATION IN X-BAND -- BEYOND 100 MW

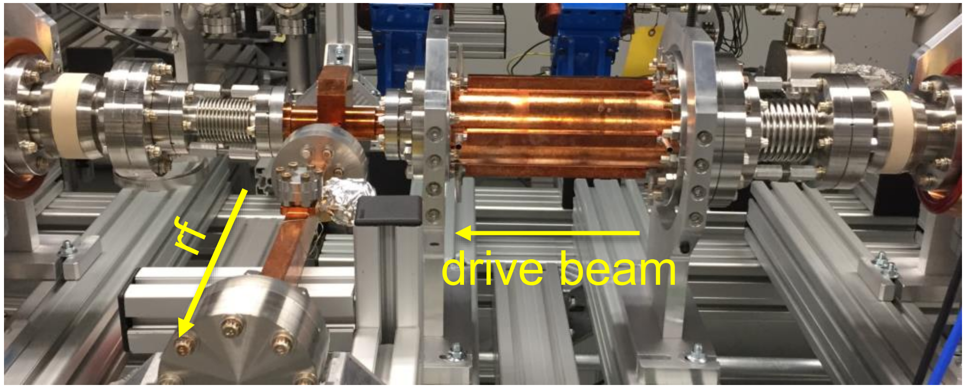
STRUCTURE OVERVIEW

- **A X-band Structure to obtain high power at AWA**
  - Large iris: ensure good transmission with high charge, minimize damage from beam irradiation



Frequency (GHz)	11.7 (9 x 1.3)
ID / OD (mm)	14.99 / 18.79
Dielectric constant	9.8 (Alumina)
Cu coating	Yes, 1 μm
Group velocity	0.1959 c
r/Q (Ω/m)	4320
Q	3392



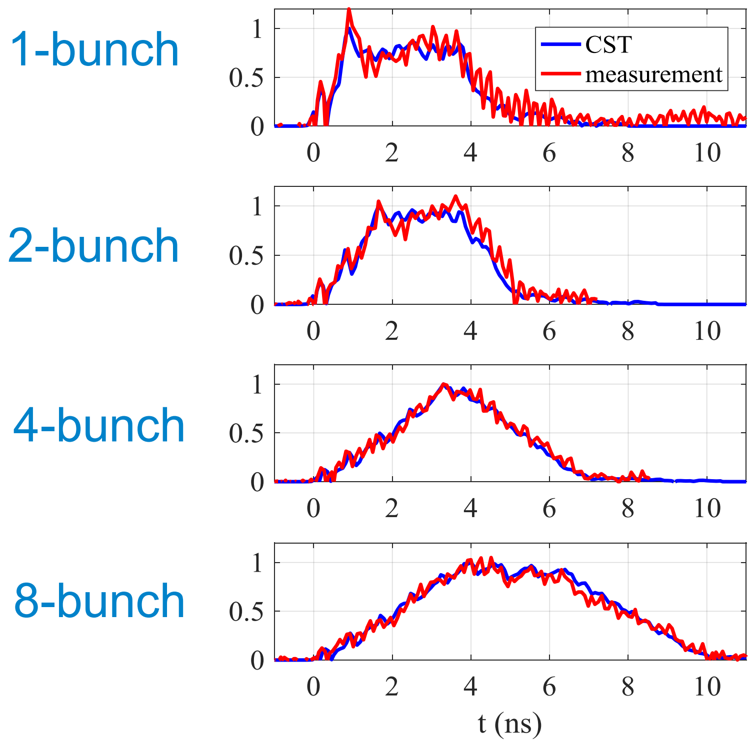


J. Shao *et al.*, in *Proc. IPAC'2018*, TUPML007, 2018

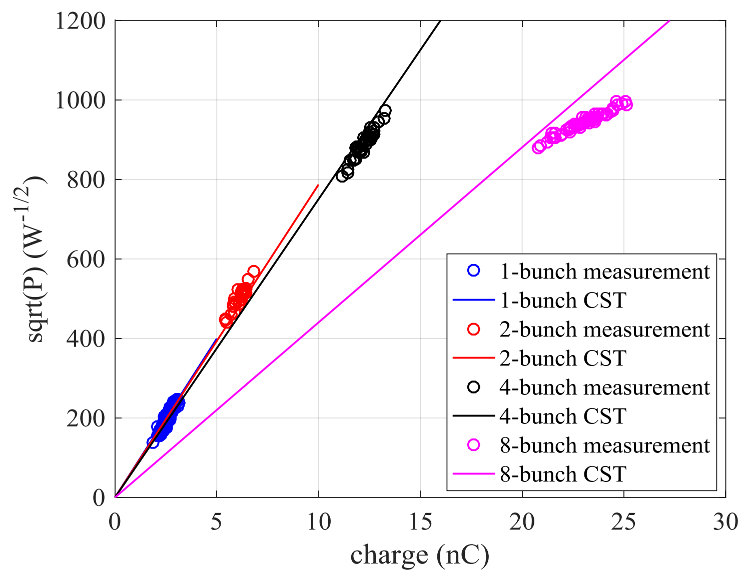
HIGH POWER TEST

- **Low charge**

  - Perfect agreement between simulation and measurement



$$\sqrt{P} = \sqrt{\frac{\omega}{4}\frac{r}{Q} vg}\, \frac{F}{1-\beta_g} Q_b$$



- **High charge**

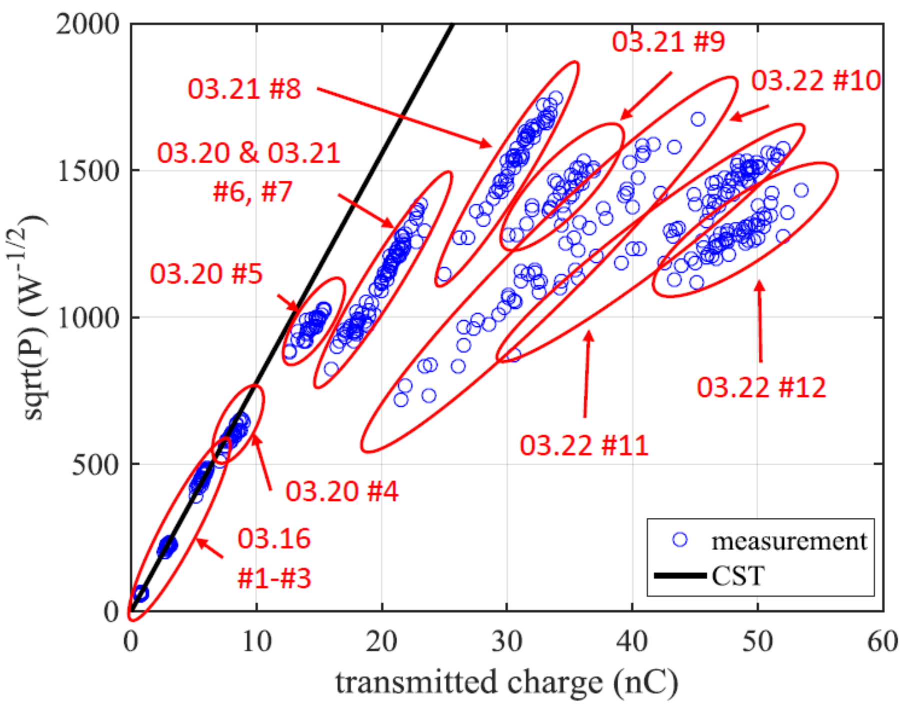
  - **90 MW** for 4-bunch train, **105 MW** for 8-bunch train

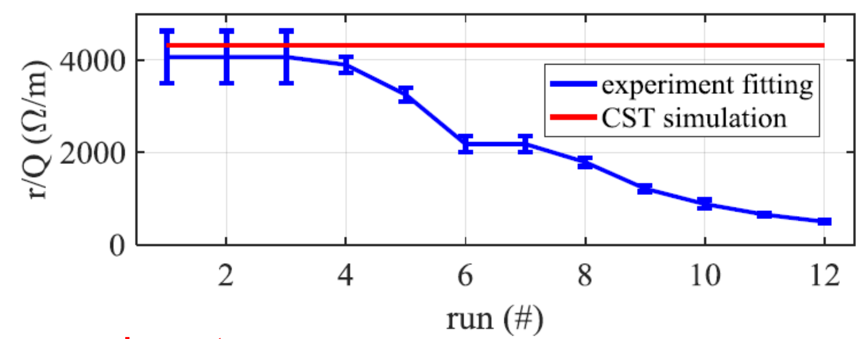
STRUCTURE COATING DAMAGE

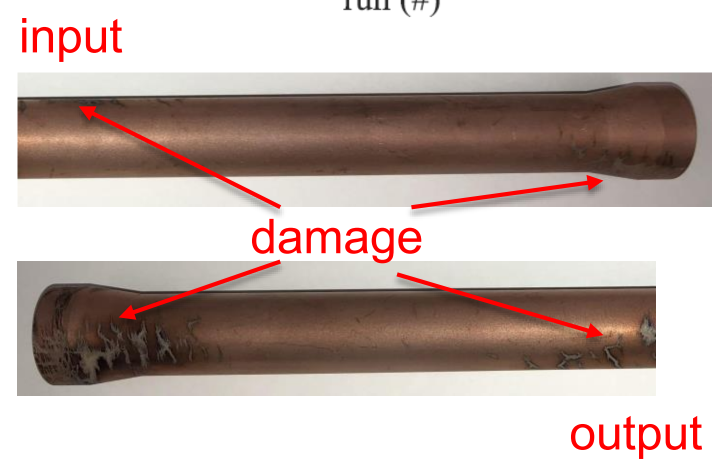
Argonne NATIONAL LABORATORY

- **Sign of structure damage during high power test**

  - Gradual degrading performance







- **Structure inspection**

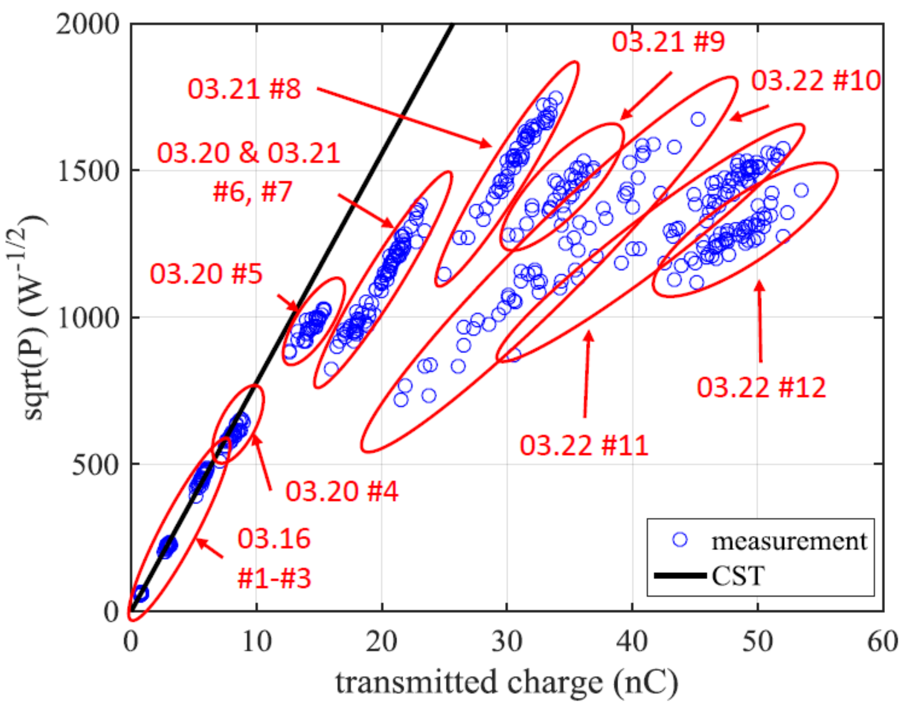
  - Transmission drops from -2.5 dB (before) to -32.5 dB (after)

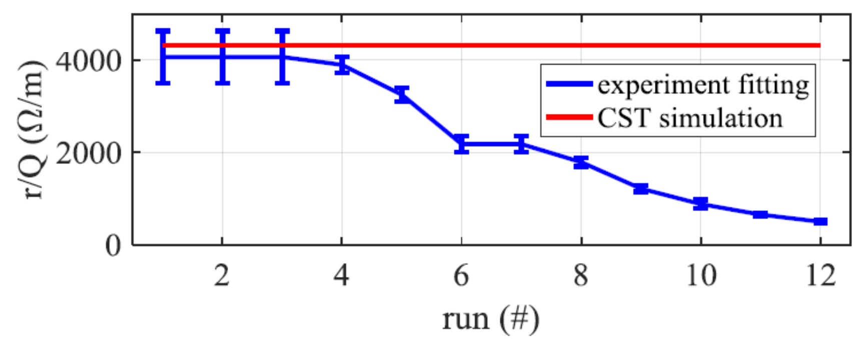
  - **Dielectric survive**, severe damage to the thin copper coating

STRUCTURE COATING DAMAGE

- **Sign of structure damage during high power test**

  - Gradual degrading performance





Thick copper coating (>100 μm) is critical for dielectric structures!

- **Structure inspection**

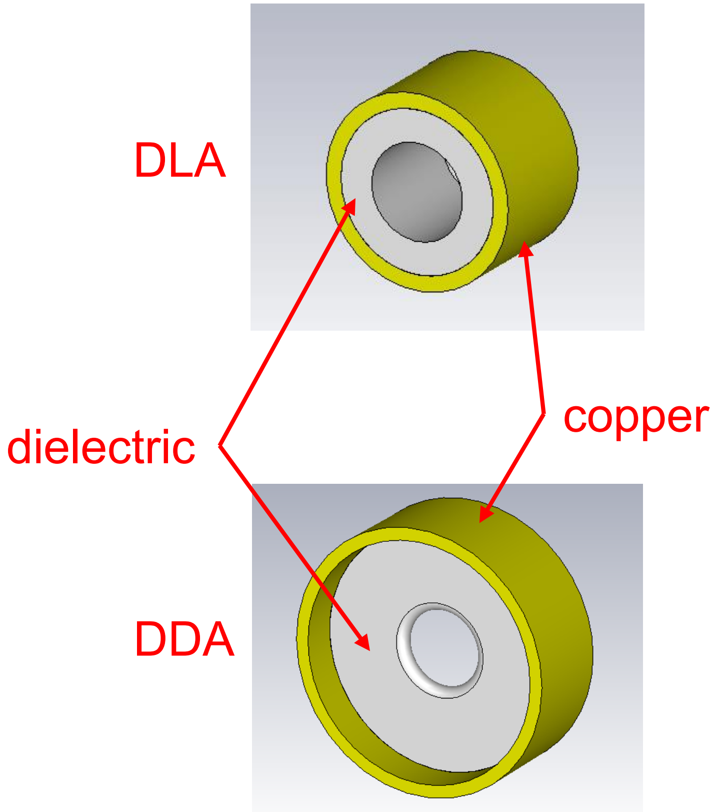
  - Transmission drops from -2.5 dB (before) to -32.5 dB (after)

  - **Dielectric survive**, severe damage to the thin copper coating

DIELECTRIC DISK ACCELERATOR -- EFFICIENCY IMPROVEMENT

STRUCTURE OVERVIEW

Argonne NATIONAL LABORATORY



	DLA	DDA
Frequency (GHz)	26	26
ID (mm)	3	3
Diel.constant	9.8	50
Diel. loss tangent	1×10^{-4}	5×10^{-4}
Group velocity	0.11 c	0.16 c
r/Q (kΩ/m)	21.8	32.5
Q	2295	6430
r (MΩ/m)	50.0	208.8
Input power (GW)	1.22	0.96
$\eta_{rf\text{-}beam}$ (%)	~9	~13
E_{max} (MV/m)	365	660
Beam loading (%)	15.5	17.1

- **Advantages of (DDA) over (DLA) for short pulse TBA**

- High efficiency (**~45%** improvement with 2π/3 mode)

- Easier machining and tuning for high frequency and constant gradient

J. Shao *et al.*, in *Proc. IPAC'2018*, TUPML005, 2018

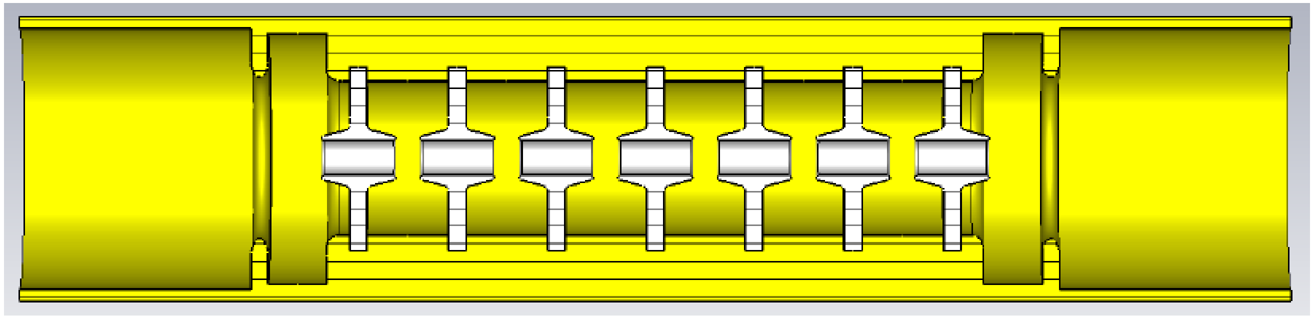
ONGOING RESEARCH

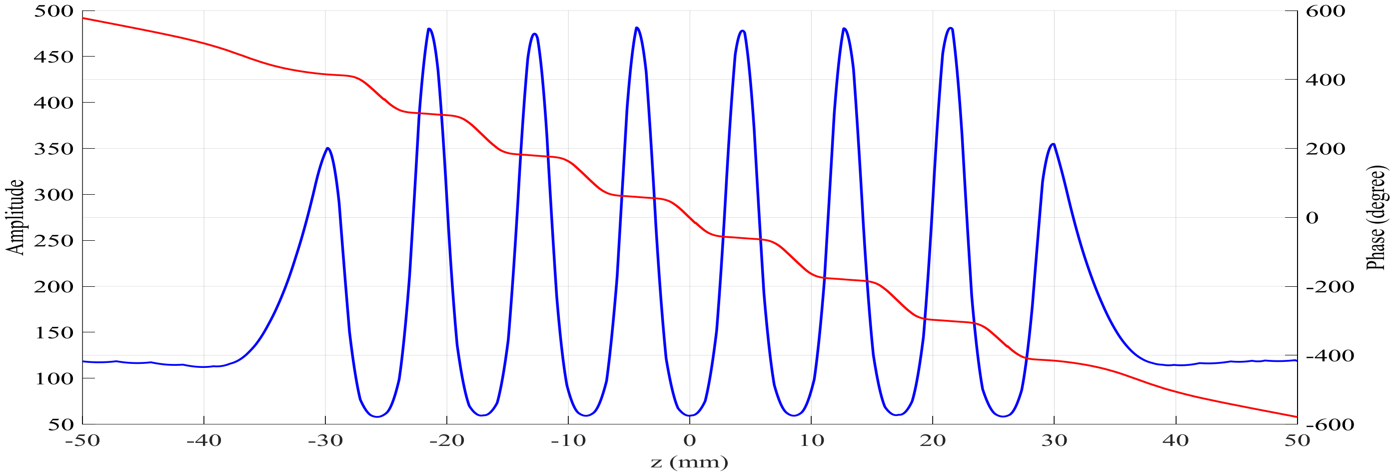
- **PETS driven X-band prototype**

 - Test brazing between dielectric and copper

 - Demonstrate machining and tuning

 - High power test to reach ultra-high surface field (nosecone for 600 MV/m)

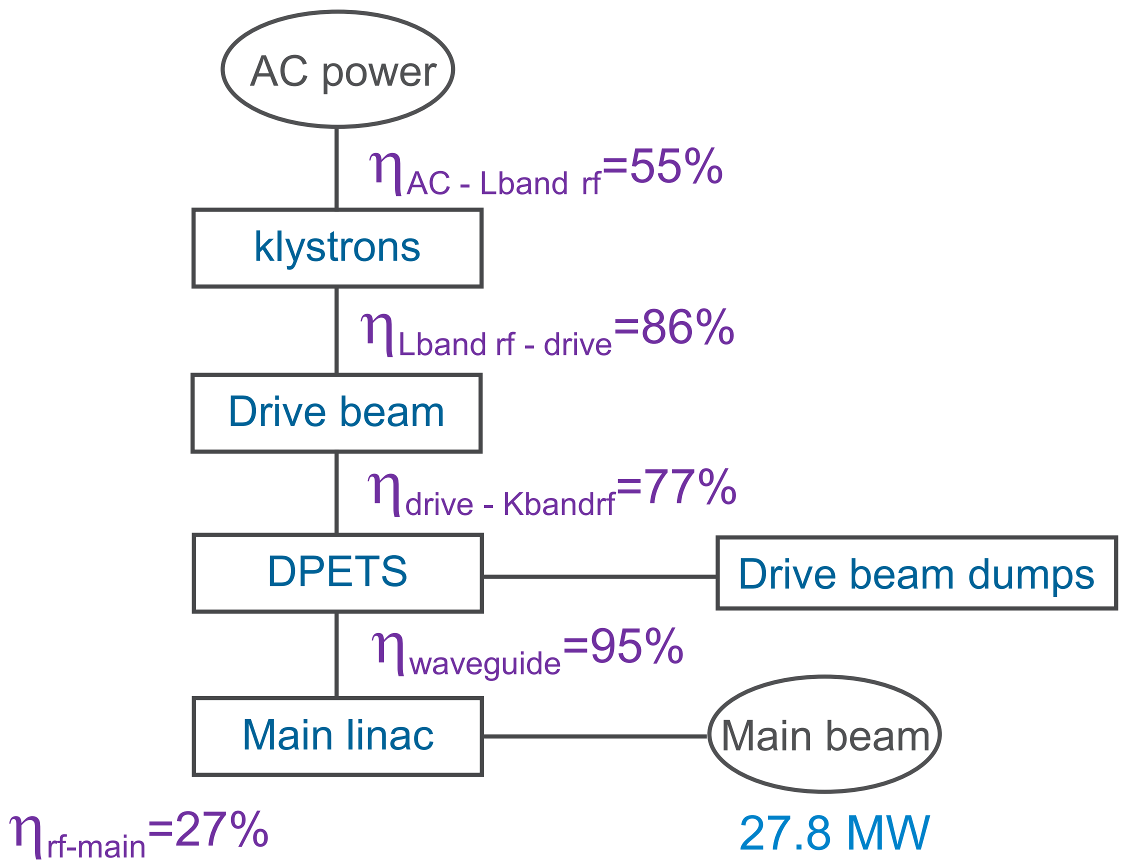




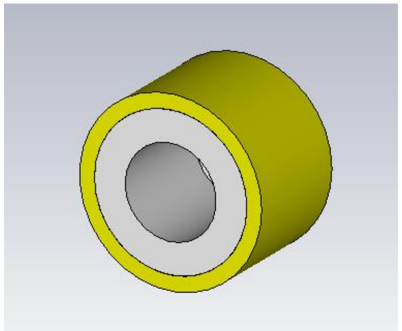
AFLC EFFICIENCY MAP

$\eta_{AC\text{-}beam}=9.4\%$

297 MW



Baseline design



Only rf power is taken into consideration

AFLC EFFICIENCY MAP

$\eta_{AC\text{-}beam}$=9.4% → 13.4%

297 MW → 207 MW

AC power

$\eta_{AC\ -\ Lband\ rf}$=55%

klystrons

$\eta_{Lband\ rf\ -\ drive}$=86%

Drive beam

$\eta_{drive\ -\ Kbandrf}$=77%

DPETS — Drive beam dumps

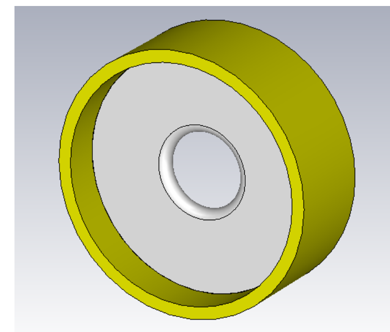
$\eta_{waveguide}$=95%

Main linac — Main beam

$\eta_{rf\text{-}main}$=27% → 39%

27.8 MW

DDA



Only rf power is taken into consideration

AFLC EFFICIENCY MAP

$\eta_{AC\text{-}beam}$=9.4% → 13.4% → 20.1%

297 MW → 207 MW → 138 MW

AC power

$\eta_{AC\text{ - }Lband\ rf}$=55%

klystrons

$\eta_{Lband\ rf\text{ - }drive}$=86%

Drive beam

$\eta_{drive\text{ - }Kbandrf}$=77%

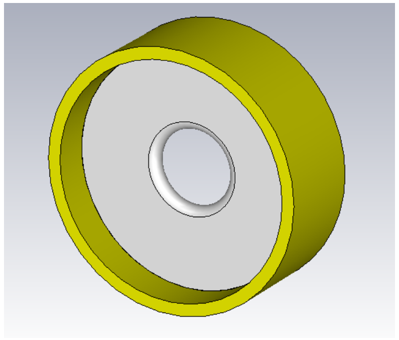
DPETS — Drive beam dumps

$\eta_{waveguide}$=95%

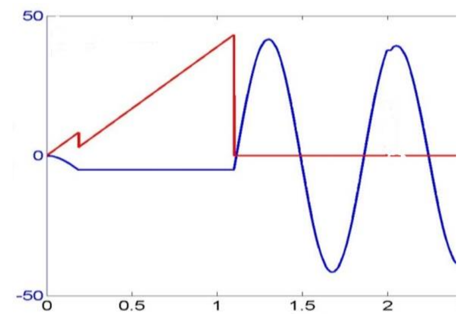
Main linac — Main beam

$\eta_{rf\text{-}main}$=27% → 39% → 58%   27.8 MW

DDA



+ Main beam shaping



Only rf power is taken into consideration

AFLC EFFICIENCY MAP

$\eta_{AC\text{-}beam}$=9.4% → 13.4% → 20.1% → 33.0%

297 MW → 207 MW → 138 MW → 84 MW

AC power

$\eta_{AC\text{ - }Lband\ rf}$=55% → 90%

klystrons

$\eta_{Lband\ rf\text{ - }drive}$=86%

Drive beam

$\eta_{drive\text{ - }Kbandrf}$=77%

DPETS — Drive beam dumps

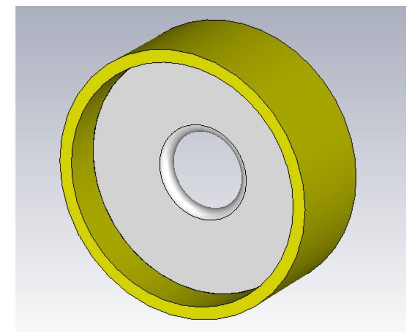
$\eta_{waveguide}$=95%

Main linac — Main beam

$\eta_{rf\text{-}main}$=27% → 39% → 58%

27.8 MW

DDA



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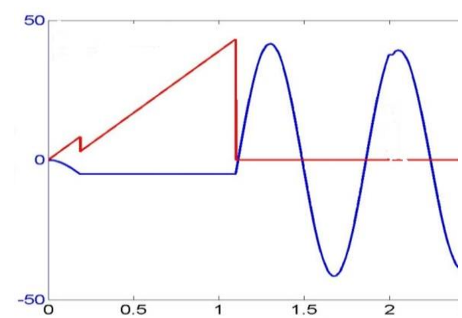


+ High efficiency klystron

Only rf power is taken into consideration

SUMMARY

- **Short pulse dielectric TBA**
  - A promising candidate which may meet the requirements of high gradient, high efficiency, and low fabrication cost of a future linear collider

- **Short pulse dielectric TBA at AWA**
  - K-band: 55 MW generated power, 28 MeV/m acceleration
  - X-band: 105 MW generated power

- **Dielectric disk structure**
  - An alternative structure to remarkably improve the efficiency
  - 33% AC to main beam efficiency with other advanced technologies

FUTURE STUDY

- **Dielectric power extractor**

  - High power test with thick coating

  - Other limiting factors

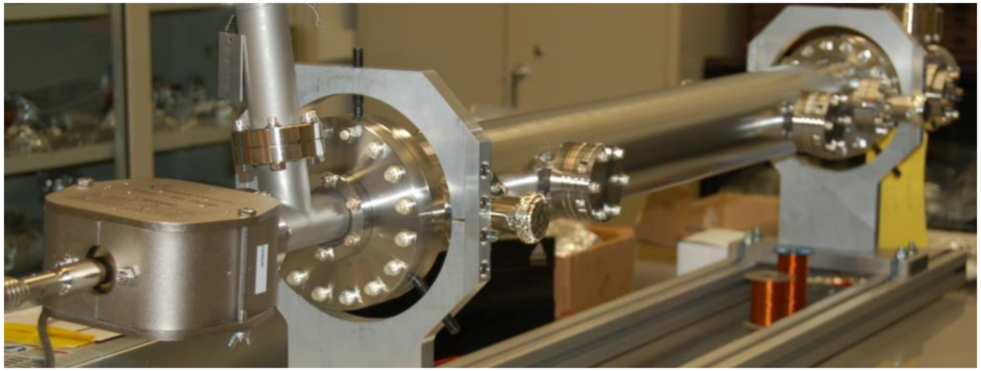
- **Dielectric accelerator**

  - High power test for higher gradient

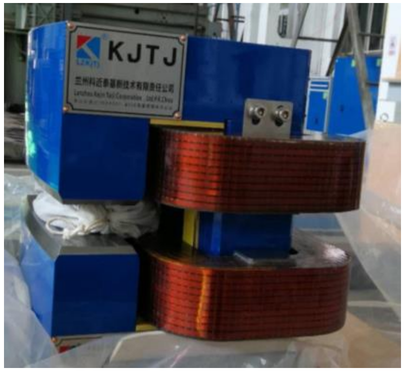
  - DDA

- **Short pulse TBA**

  - full staging with kicker and septum



kicker



septum from IMP

ACKNOWLEDGEMENT

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