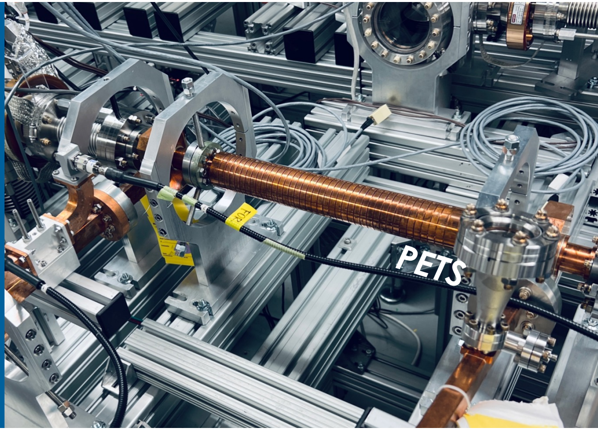
SHORT-PULSE SWFA MODULES FOR 10 TeV COLLIDER APPLICATIONS



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01/26/2026

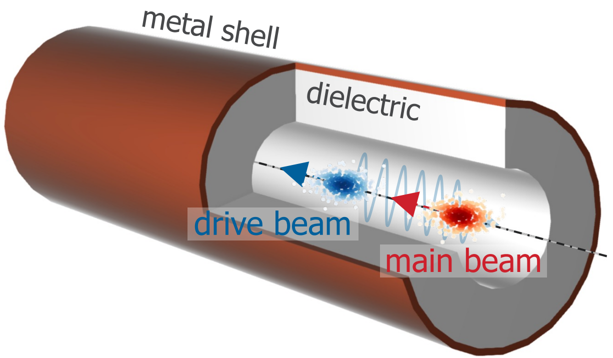
OUTLINE

- Introduction to Structure Wakefield Acceleration (SWFA)
- AWA current capabilities, and TBA concept
  - Strong X-band foundations
- Achieving luminosity via SWFA approach
- Performance metrics for a single TBA module (PETS+LINAC)
- Future work and challenges

STRUCTURE WAKEFIELD ACCELERATION

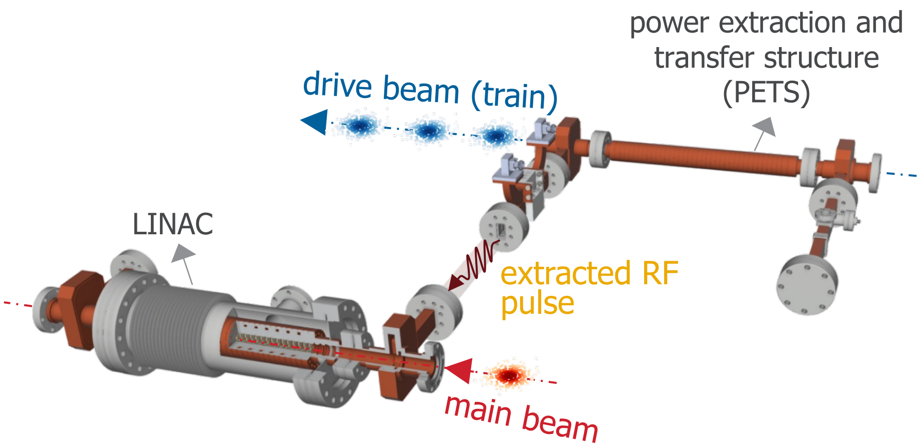
CWA and TBA

Collinear Wakefield Acceleration (CWA)



- Drive and main beam propagate in the same structure.
- Energy transferred locally to trailing bunch.

Two Beam Acceleration (TBA)



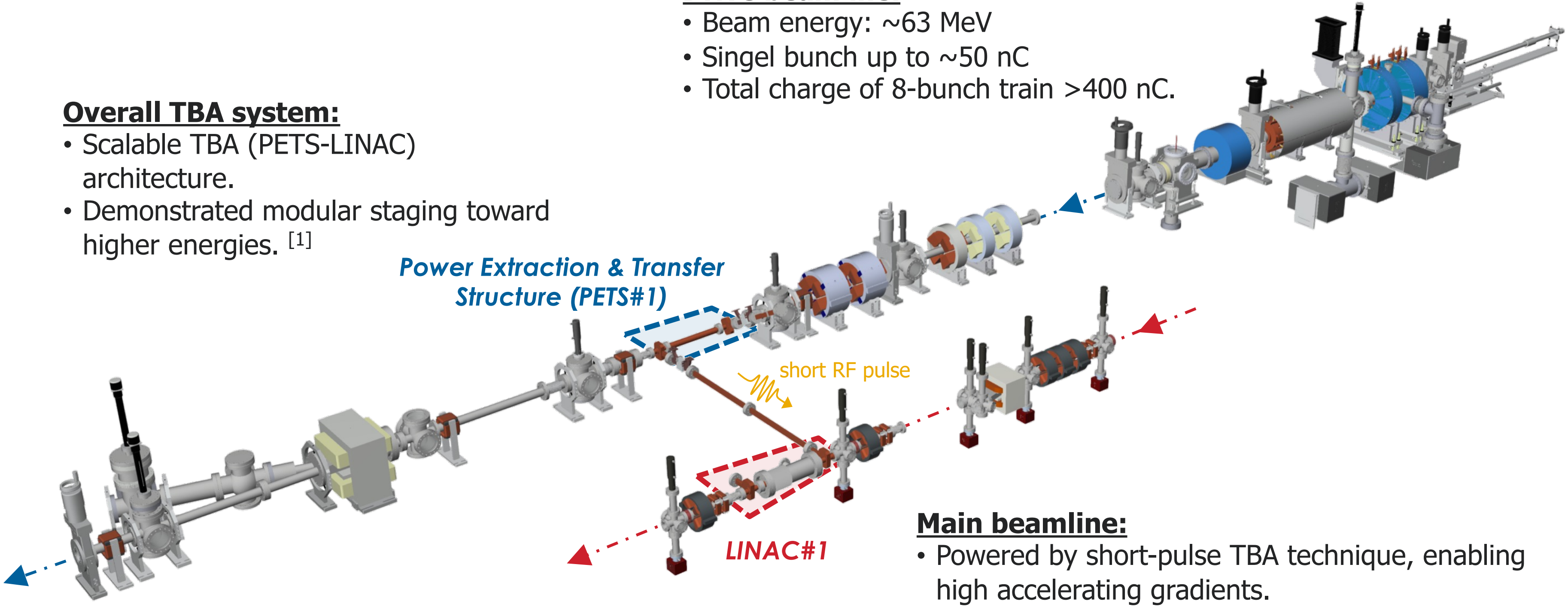
- Drive and main beams propagate in separate beamlines and different structures.
- RF power is extracted from the drive beam and transferred to the main beamline.

SWFA ARCHITECTURE

Based on modular TBA units

Drive beamline:
- Beam energy: ~63 MeV
- Singel bunch up to ~50 nC
- Total charge of 8-bunch train >400 nC.

Overall TBA system:
- Scalable TBA (PETS-LINAC) architecture.
- Demonstrated modular staging toward higher energies. [1]



Main beamline:
- Powered by short-pulse TBA technique, enabling high accelerating gradients.
- Extracted RF power >500 MW from an X-band PETS.

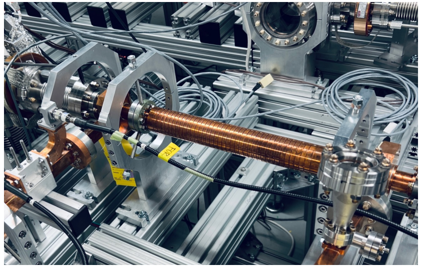
[1] C. Jing, et al, NIMA 898, 72-76 (2018)

SYSTEM OVERVIEW AND DESIGN CONTEXT

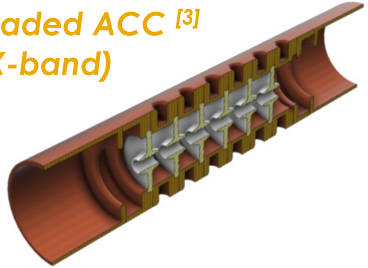
Quick background

- **Core idea:** short-pulse (~10 ns) TBA
- **Major components:**
  1. Drive beam: with high charge, high energy, high rep rate etc.
  2. PETS: for short-pulse generation
  3. LINAC: for main beam acceleration
- **Current status:**
  - We have established a strong foundation on X-band structures, including general RF components (e.g. power splitters, and phase shifters etc.), metallic and dielectric PETS and LINACs.
  - In-house high power conditioning test-stand, and a dedicated main beamline for R&D.

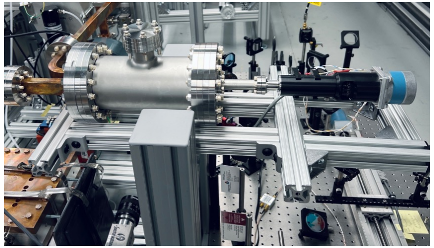
Metallic PETS [1] (X-band)



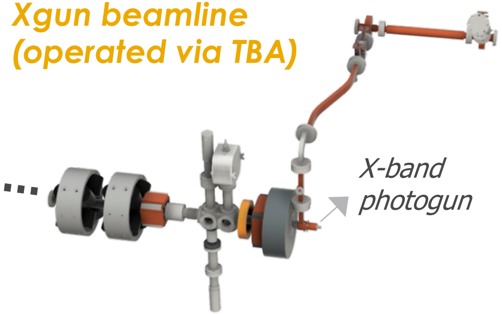
Dielectric Disk-loaded ACC [3] (X-band)



Phase shifter [2] (X-band)



Xgun beamline (operated via TBA)



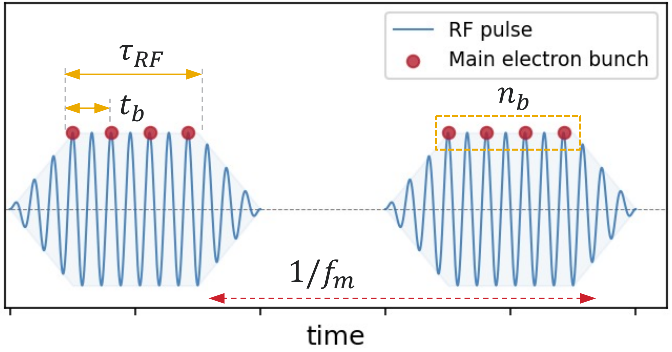
[1] J. Shao et. al., doi:10.18429/ JACoW- IPAC2019- MOPRB069 (2019)
[2] S. Kuzikov et. al., doi:10.18429/JACoW-IPAC2022-MOPOMS013 (2022)
[3] J. Shao, et al., doi: 10.18429/JACoW-IPAC2018-TUPML005 (2018)

ACHIEVING LUMINOSITY VIA SWFA APPROACH

In the SWFA context:

- PETS serves as the RF power for the LINAC in the main beamline. RF pulse duration (τ_{RF}) is controlled by the drive bunch-train configuration.
- Short RF pulses (~10 ns) enable low BDR and high-gradient operation.
- Then, the short RF pulses generated from PETS will be fed to the LINAC and boost the main beam.
- To achieve high $\mathcal{L}$, the main beam config (i.e. macro pulse format) needs to be carefully studies.

Macro pulse format



Given the geometric luminosity:

$$\mathcal{L} = \frac{n_b f_m N^2}{4\pi\sigma_x\sigma_y}$$

where, n_b- number of bunches per RF pulse
N- number of particles in one bunch (bunch charge $Q_b = eN$)

$$n_b f_m = \frac{\tau_{RF} f_{RF}}{k} * f_m$$

RF pulse length (~10 ns)

Main linac *f*
Higher f is preferred, as it increases n_b with fixed τ_{RF}.

Rep. rate

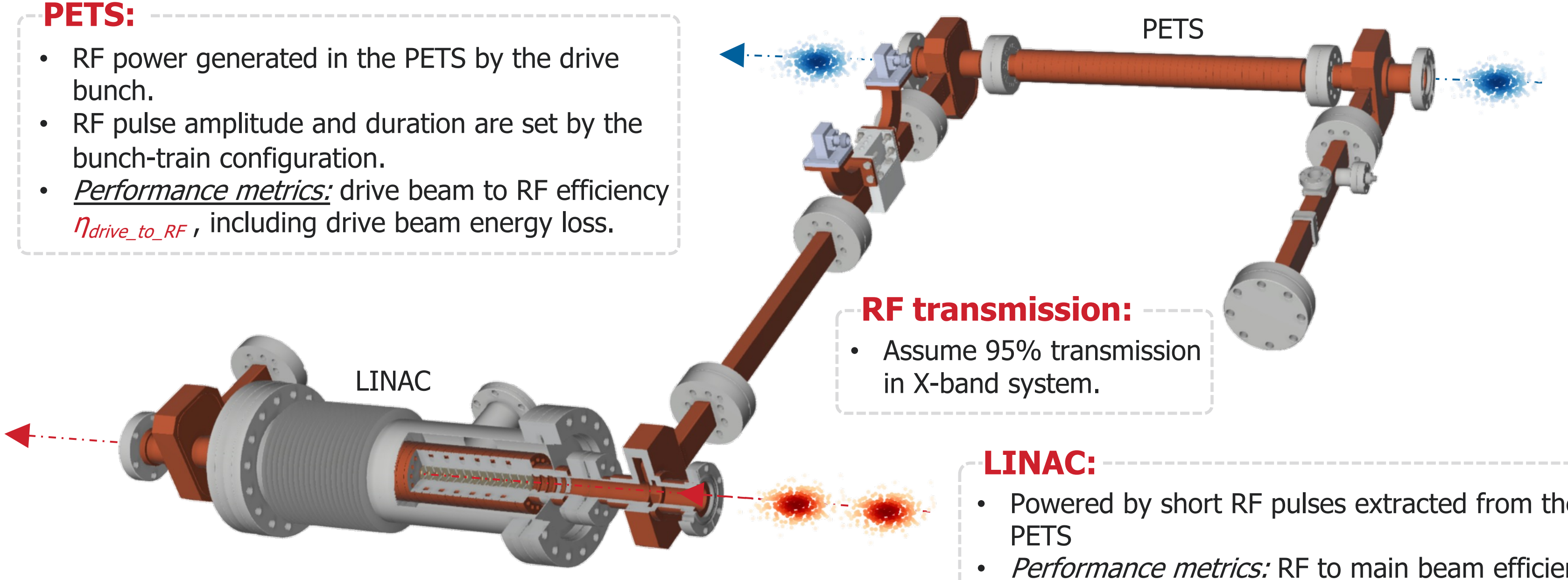
Bunch separation related
$t_b = k/f_{RF}$

EFFICIENCY CHAIN IN ONE TBA MODULE

Drive beam ⇒ RF power ⇒ main beam energy gain

PETS:

- RF power generated in the PETS by the drive bunch.
- RF pulse amplitude and duration are set by the bunch-train configuration.
- *Performance metrics:* drive beam to RF efficiency $\eta_{drive\_to\_RF}$, including drive beam energy loss.



RF transmission:

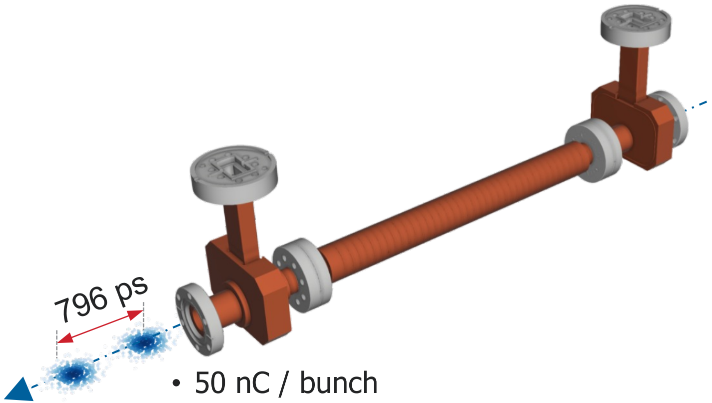
- Assume 95% transmission in X-band system.

LINAC:

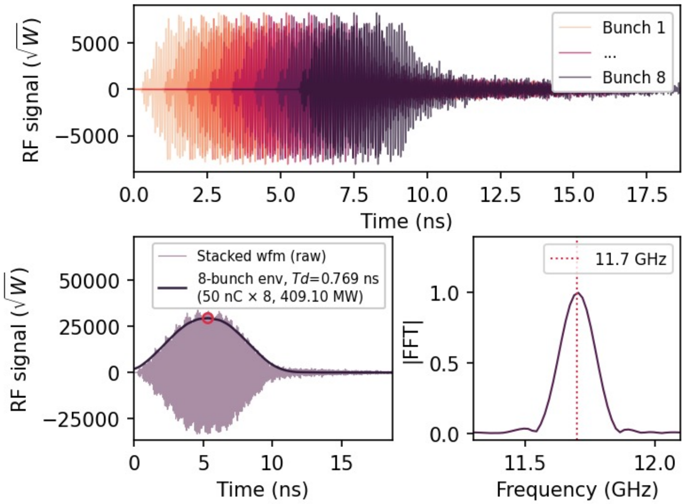
- Powered by short RF pulses extracted from the PETS
- *Performance metrics:* RF to main beam efficiency $\eta_{RF\_to\_main}$, including main beam energy gain, beam loading, RF pulse utilization.

STUDIES ON PETS
RF power generation

- **Principle:** coherent stacking of wakefield pulse produced by bunches within a train
  - Routinely generate power >500 MW at 11.7 GHz.
  - RF pulse duration can be adjusted though different bunch train configuration.



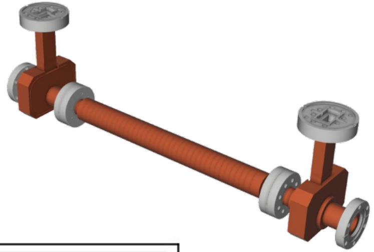
- 50 nC / bunch
- Total of 8 bunches



X-band PETS (ID=17.6 mm | L=30 cm)	
r/Q	3920 Ω/m
Q	6500
Vg/c	0.22
Drive bunch length (σ_z)	1 mm
Drive bunch spacing (t_b)	796 ps
Drive bunch charge (Q_b)	50 nC
# of bunches in train	8
Power	~400 MW
T_{RF} (FWHM)	~6 ns

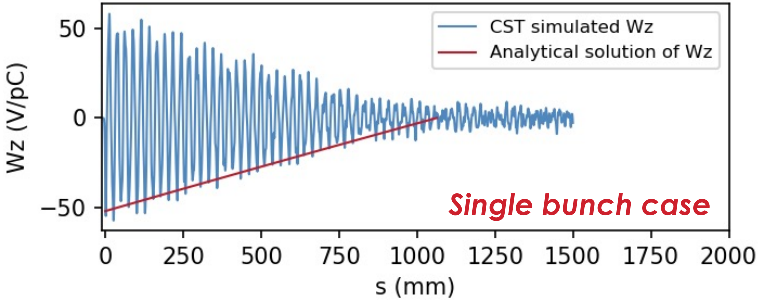
STUDIES ON PETS

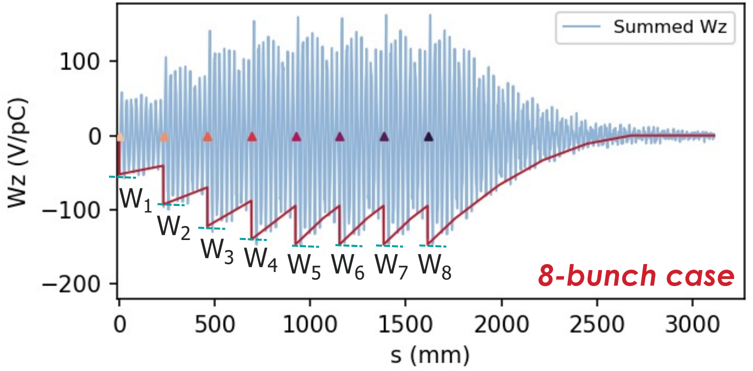
Energy loss and $\eta_{drive\_to\_RF}$



- **Drive beam energy loss:** coherent wakefields in the PETS convert drive-beam energy into RF power, with the associated beam energy loss.
- **Drive-to-RF efficiency ($\eta_{drive\_to\_RF}$):** measures how effectively the beam's energy loss is converted into RF output.

X-band PETS (ID=17.6 mm | L=30 cm)	
Drive bunch length (σ_z)	1 mm
Drive bunch spacing (t_b)	796 ps
Drive bunch charge (Q_b)	50 nC
# of bunch in train	8
Energy loss	6.03 MeV
$\eta_{drive\_to\_RF}$	>95%

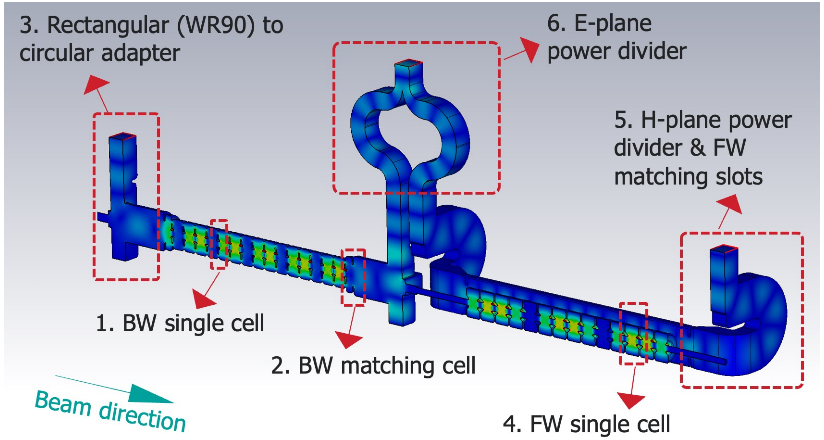


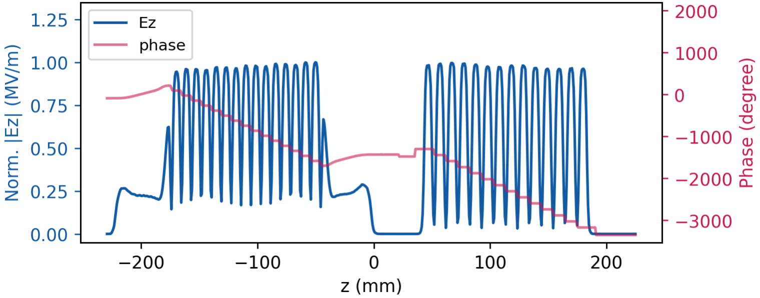


STUDIES ON LINAC
Background

- **Background on LINAC design:** To accommodate short RF pulse operation, the linac must have high group velocity (v_g) and long structure length to achieve high energy gain.
  - <u>A hybrid (BW-FW) structure</u> with longer effective length is being developed to meet this need.

X-band hybrid LINAC (ID=3.4 mm | L=30 cm | CZ)	
* r	135 MΩ/m
* Q	5000
* Vg/c	0.075
Power from PETS	~400 MW
Flat RF region (T_{beam})	6 ns
Total RF duration (T_{RF})	12.1 ns
* Listed RF parameters of the LINAC are estimated based on two halves.	





STUDIES ON LINAC

Energy gain and $\eta_{RF\_to\_main}$

Performance metrics

E-field decays w/ beam loading (CZ):

unloaded — beam term

$$E(z) = E_0 e^{-\alpha z} - rI_b(1 - e^{-\alpha z})$$

Final loaded energy gain:

$$U = \int_0^L E(z)\,dz = U_{unloaded} - U_{beam}$$

Beam-loading fraction:

$$BL(\%) = \frac{U_{beam}}{U_{unloaded}}$$

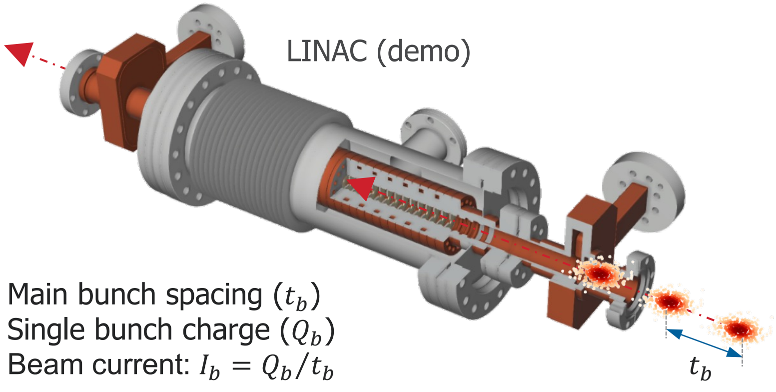
RF-to-main efficiency:

$$\eta_{RF\_to\_beam} = \frac{UI_b}{P_{in}} * \frac{T_{beam}}{T_{RF}}$$

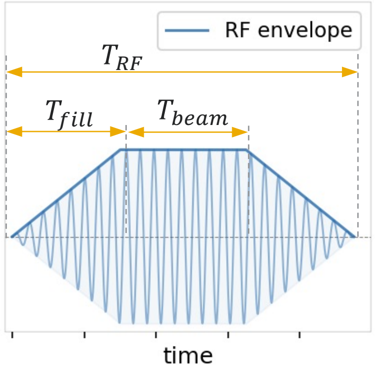
Rf pulse utilization

Step-up ratio in TBA:

$$R_{step\_up} = \frac{\text{Main beam energy gain}}{\text{Drive beam energy loss}}$$



- Main bunch spacing (t_b)
- Single bunch charge (Q_b)
- Beam current: $I_b = Q_b/t_b$



Main beam parameters (bunch charge, spacing etc.) determine energy gain, efficiency, beam loading, and ultimately luminosity.

$\mathcal{L}$ - PARAMETER-SPACE OPTIMIZATION

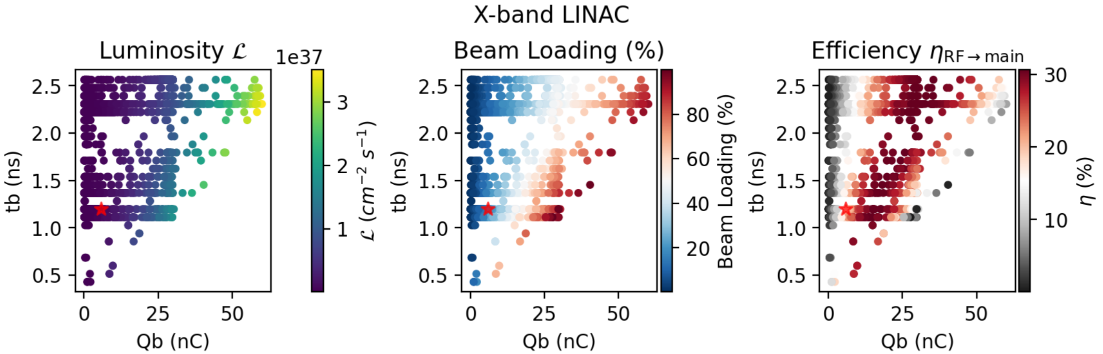
Preliminary

Given the geometric luminosity:

$$\mathcal{L} = \frac{n_b f_m N^2}{4\pi\sigma_x\sigma_y}$$

$$\mathcal{L} \propto n_b f_m N_b^2 = \tau_{RF}\frac{f_{RF}}{k} * \left(\frac{Q_b}{e}\right)^2 * f_m$$

where, $t_b = \frac{k}{f_{RF}}$, $Q_b = eN_b$, $I = \frac{eN_b}{t_b}$



Baseline luminosity ($\mathcal{L}$) optimization:

- Tuning variables: bunch spacing *k* (aka t_b), bunch charge Q_b
- Fixed parameters: f_m=100 Hz, τ_{RF}=6 ns.
- Objectives / constrains:
  - High luminosity $\mathcal{L}$
  - Reasonable BL%<30%
  - High $\eta_{RF\_to\_main}$

Selected result (preliminary):

- Q_b=5.89 nC, t_b=1.20 ns, BL%<20%, $\eta_{RF\_to\_main}$=~19%
- Main beam energy gain: ~28 MeV
- Step-up ratio: 4.6
- $\mathcal{L}$=6.52E+35 (with other beam parameters from Snowmass'21 ITF)

While encouraging, but other challenges remain…

FUTURE WORK AND CHALLENGES

- **Very near future work:** explore higher frequency structures (Ka-band PETS, Ka-band LINAC)
  - Higher power from PETS
  - Higher gradient from LINAC, and higher energy gain!
- **Drive beam production:**
  - Need to achieve high repetition rate, currently no practically good solution.
- **PETS side:**
  - BBU/MBBU, needs damping.
  - Thermal management, cooling.
- **Main beam side:**
  - Need to determine a reasonable bunch charge and separation, so not affected by the $W_\perp$.
  - BBU/MBBU, needs damping too.
  - Reasonable beam loading fraction.
  - Emittance preservation in the LINAC.
  - Thermal management, cooling.
- **Others:**
  - Power efficiency (drive ⇒ RF ⇒ main).
  - May have higher power loss in Ka-band system.

BACKUP

SNOWMASS'21 ITF

https://arxiv.org/pdf/2208.06030 (page 69)

Table 25. Parameters of the advanced WFA-based colliders.

Technology	PWFA	PWFA	PWFA	SWFA	SWFA	SWFA	LWFA	LWFA	LWFA
Aspect Ratio	Flat	Flat	Round	Flat	Flat	Round	Flat	Flat	Round
CM Energy	1	3	15	1	3	15	1	3	15
Single beam energy (TeV)	0.5	1.5	7.5	0.5	1.5	7.5	0.5	1.5	7.5
Gamma	9.78E+05	2.94E+06	1.47E+07	9.78E+05	2.94E+06	1.47E+07	9.78E+05	2.94E+06	1.47E+07
Emittance X (mm mrad)	0.66	0.66	0.1	0.66	0.66	0.1	0.1	0.02	0.1
Emittance Y (mm mrad)	0.02	0.02	0.1	0.02	0.02	0.1	0.01	0.007	0.1
Beta* X (m)	5.00E-03	5.00E-03	1.50E-04	5.00E-03	5.00E-03	1.50E-04	2.50E-02	1.40E-02	1.50E-04
Beta* Y (m)	1.00E-04	1.00E-04	1.50E-04	1.00E-04	1.00E-04	1.50E-04	1.00E-04	1.00E-04	1.50E-04
Sigma* X (nm)	58.07	33.53	1.01	58.07	33.53	1.01	50.55	9.77	1.01
Sigma* Y (nm)	1.43	0.83	1.01	1.43	0.83	1.01	1.01	0.49	1.01
N_bunch (num)	5.00E+09	5.00E+09	5.00E+09	3.13E+09	3.13E+09	3.13E+09	1.20E+09	1.20E+09	7.50E+09
Freq (Hz)	4200	14000	7725	11000	36000	19800	46856	46856	3435
Sigma Z (um)	5	5	5	40	40	40	8.4	8.4	2.2
Beamstrahlung parameter	15	78	6590	1	6	515	2	37	22466
n_γ	1.5	1.5	5.7	2.2	2.2	8.4	0.8	1.5	5.7
Single Beam Power (MW)	1.7	16.8	46.4	2.8	27.0	74.4	4.5	13.5	31.0
Two Beam Power (MW)	3.4	33.6	92.8	5.5	54.1	148.7	9.0	27.0	61.9
Geometric Lumi (cm^{-2} s^{-1})	1.01E+34	1.01E+35	1.50E+36	1.03E+34	1.01E+35	1.51E+36	1.05E+34	1.13E+35	1.50E+36
Beamstrahlung lumi	1.99E+34	1.99E+35	1.52E+36	2.03E+34	2.00E+35	1.52E+36	2.09E+34	2.17E+35	1.52E+36
Wall plug to drive laser/beam eff	0.4	0.4	0.4	0.774	0.774	0.774	0.4	0.4	0.5
Laser/beam drive to main eff	0.375	0.375	0.375	0.42	0.42	0.42	0.2	0.2	0.12
Wall plug to main beam eff	0.15	0.15	0.15	0.32508	0.32508	0.32508	0.08	0.08	0.06
Site power Wall to main only (MW)	22	224	619	17	166	457	113	338	1032
Lumi/Power (1e34/MW)	0.04	0.04	0.08	0.06	0.06	0.11	0.01	0.03	0.05
GUINEA-PIG Total Lumi	1.83E+34	1.85E+35	4.2E+37	2.08E+34	2.13E+35	4.2E+36	1.53E+34	2.58E+35	6E+36
GUINEA-PIG Lumi 1% (20%)	6.86E+33	6.23E+34	5E+35	8.49E+33	6.14E+34	5E+35	1.03E+34	8.72E+34	5E+35
GP Total Lumi/Power	0.08	0.08	6.79	0.12	0.13	0.92	0.01	0.08	0.58
GP Lumi 1%/Power (20%)	0.03	0.03	0.08	0.05	0.04	0.11	0.01	0.03	0.05
Length of 2 Linacs (km)	1	3	14	5	15	75	0.44	1.3	6.5
Length of Facility	14	14	14	8	18	90	3.5	4.5	9.5