Experiment on the interaction of electron bunch train with a W-band wakefield structure at AWA: high power and high gradient

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On behalf of the AWA and Euclid group

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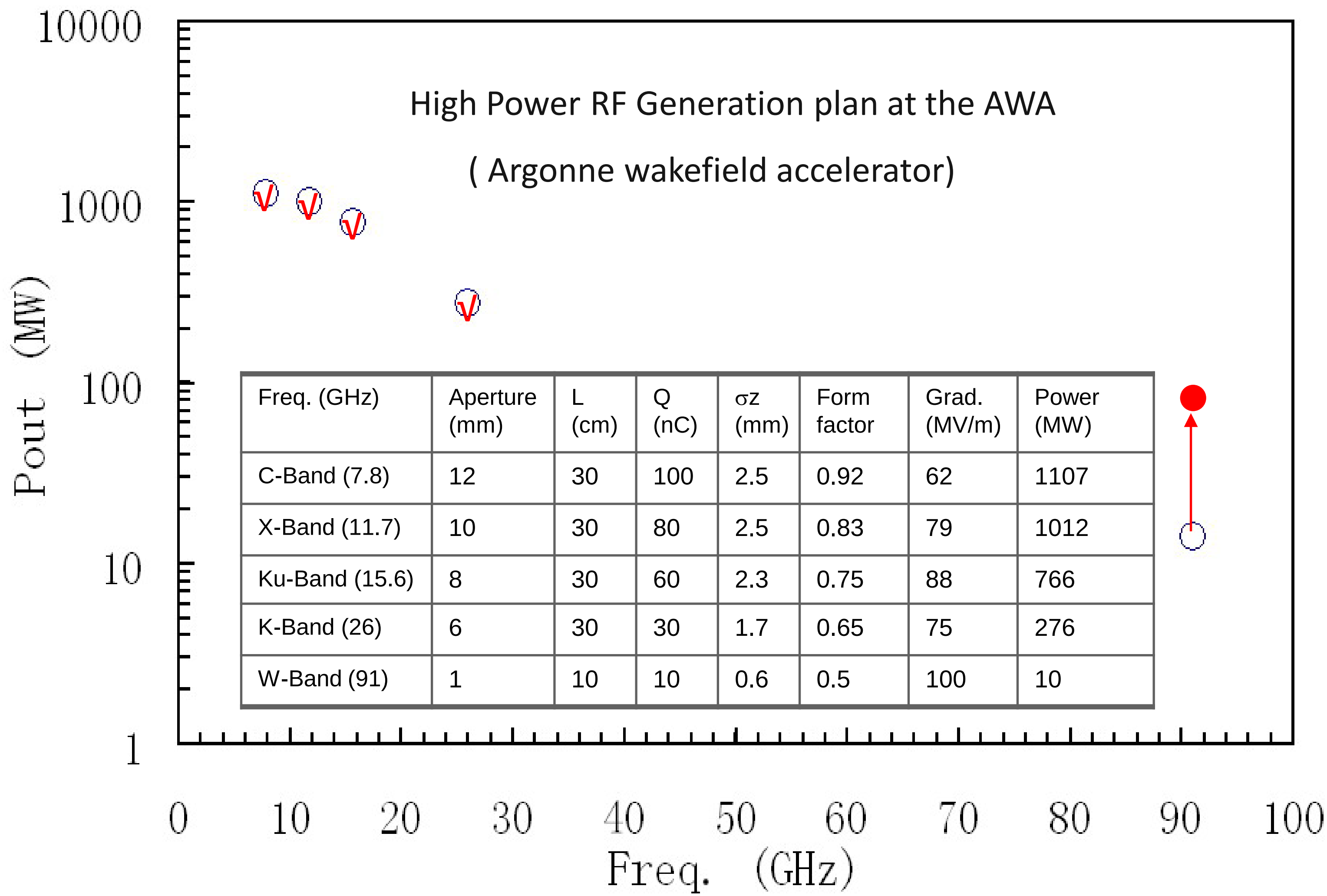
Outline

- Motivation
- Method
- Single bunch experiment
- Bunch train experiment
- Summary

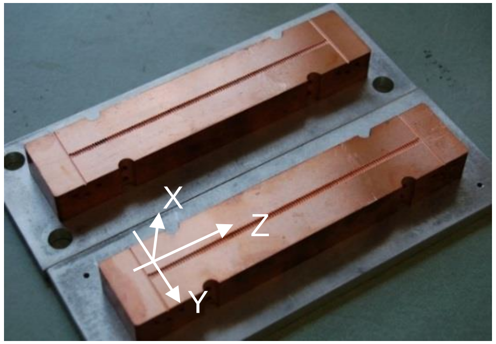
Motivation: AWA map

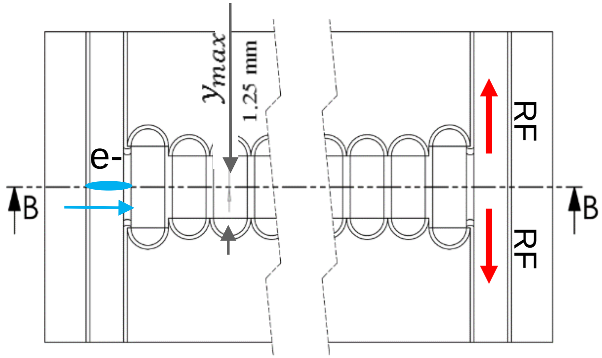


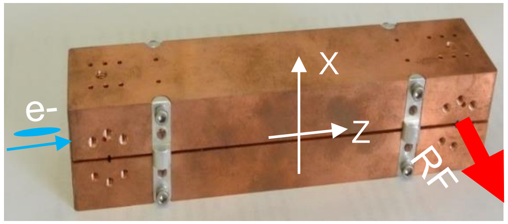
Freq. (GHz)	Aperture (mm)	L (cm)	Q (nC)	σz (mm)	Form factor	Grad. (MV/m)	Power (MW)
C-Band (7.8)	12	30	100	2.5	0.92	62	1107
X-Band (11.7)	10	30	80	2.5	0.83	79	1012
Ku-Band (15.6)	8	30	60	2.3	0.75	88	766
K-Band (26)	6	30	30	1.7	0.65	75	276
W-Band (91)	1	10	10	0.6	0.5	100	10

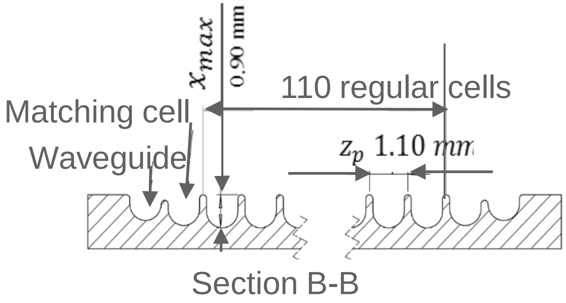
Method: design of the W-band* PETS

Power Extraction and Transfer Structure : PETS









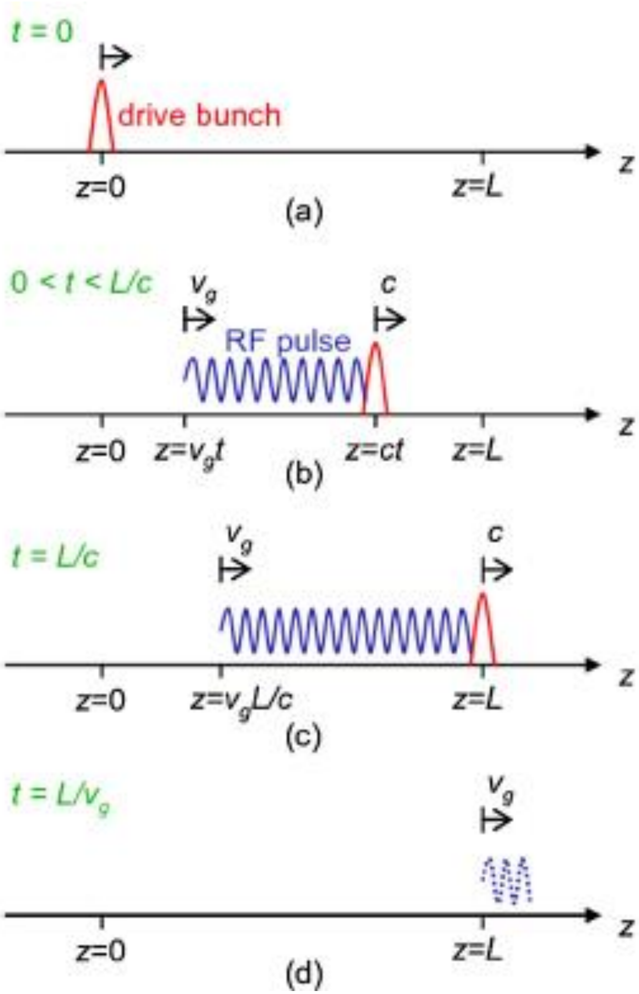
Total length of the grooved structure : 12 cm

When fixed the gap = 0.94 mm : $f_0 = 91\ GHz,\ \ \lambda_0 = 3.3\ mm$

70th harmonic of L-band (1.3 GHz) RF at the AWA

* Similar to Valery Dolgashev (SLAC) 100 GHz structure

Method: wakefield (RF) generated by single bunch



Duration of rf pulse:

$$\tau_s = \frac{L}{v_g} - \frac{L}{c}$$

$3.4[ns]$

Gradient in the structure :

$$E_s = 2k_L q_b F(\sigma_z)$$

$26.6[MV/m/nC] \cdot F(\sigma_z) \cdot q_b$

RF power :

$$P_s = \frac{E_s^{\,2} v_g}{4k_L(1-\beta_g)}$$

Method: enhance power with drive bunch train

RF bucket with adjustable time structure :

T_b: bunch spacing

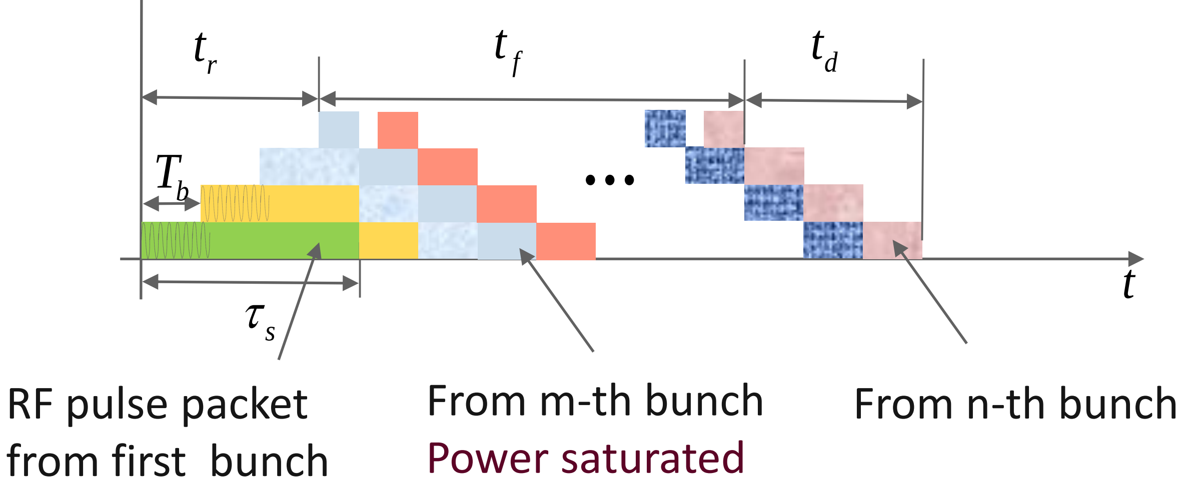
$$m = \text{ceiling}\left(\frac{\tau_s}{T_b}\right)$$

$$E_t = mE_s$$

$$t_r = (\text{m}-1)\times T_b$$

$$\tau_f = (n-1)\times T_b + \tau_s - 2t_r$$

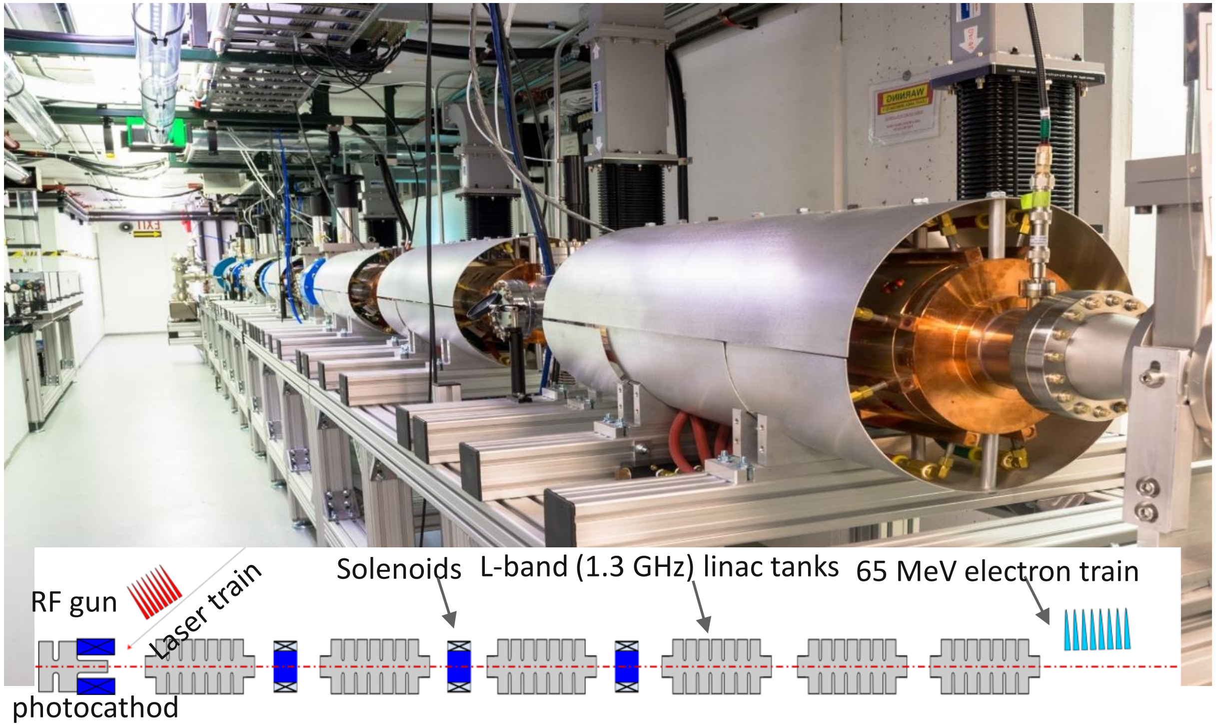
$$t_d = t_r$$



Total RF peak power: $P_f \propto (mE_s)^2$

Method: drive beam line at AWA

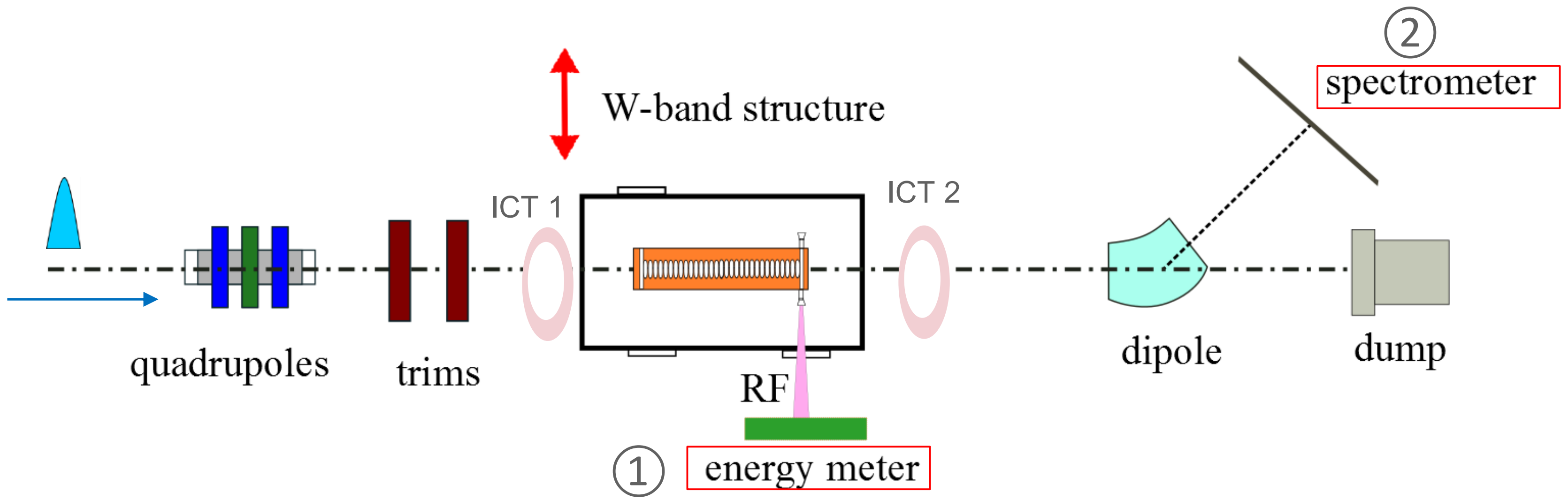
Single (sub) bunch charge: q_b	**5 nC**	**10 nC**
Bunch RMS length: σ_z (mm)	0.50	0.60
Formfactor at 91 GHz: F(σ_z)	0.60	0.37
RMS beam size: σ_x (mm)	0.2	0.35



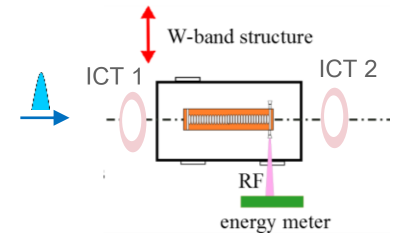
Single bunch experimental set up

Detectors :

- 1. Energy meter (calibrated): RF output energy
- 2. Spectrometer: energy loss of electron beam

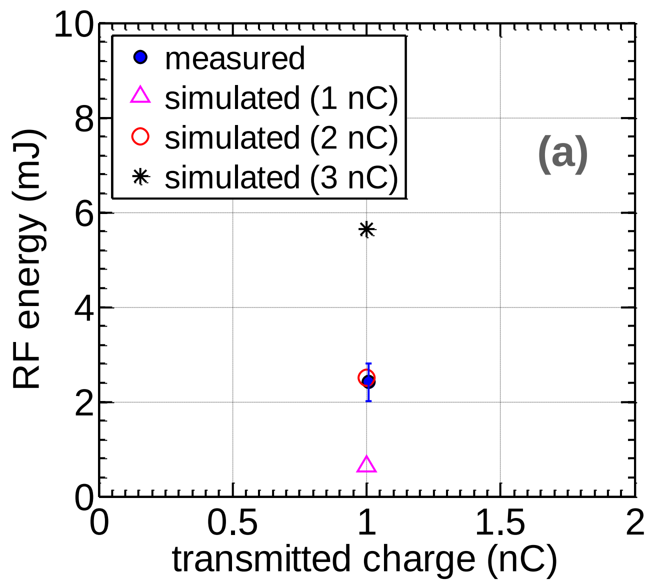


Single bunch experimental results_(1)

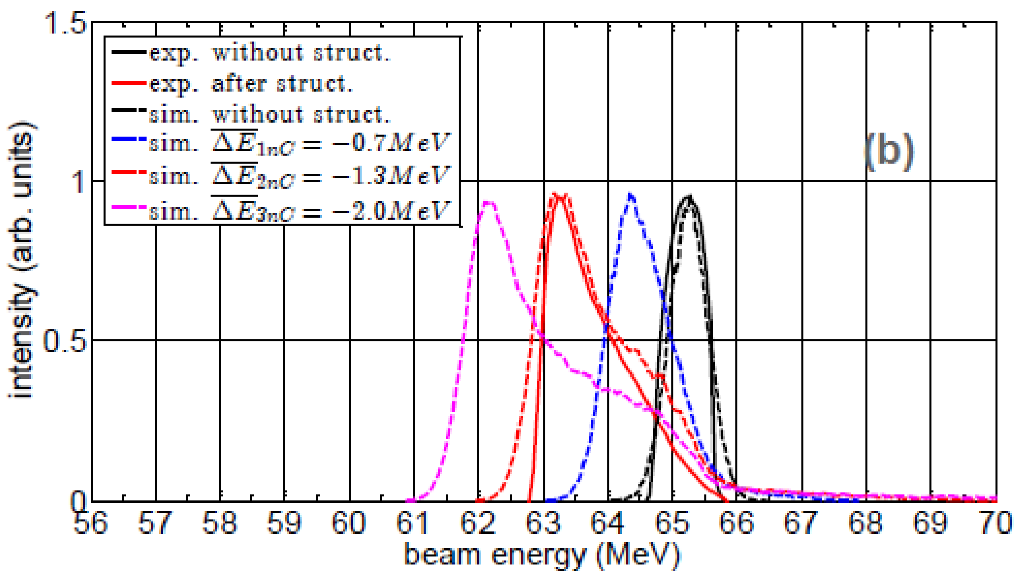


'effective charge': charge contribute to the wakefield

RF simulation code: CST



Beam dynamics simulation code: ASTRA



Charge before structure (ICT 1): 3nC

Transmitted charge after (ICT 2): 1nC

Effective charge convert to the RF: 2nC

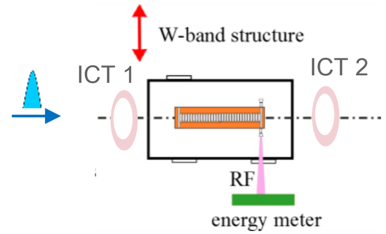
Charge of the drive bunch → average loss

2.6 mJ (Fig.a) = 1.3 MeV (Fig.b) * 2nC

energy conservation : beam energy loss = RF output

RF: 0.77 MW * 3.4 ns

Single bunch experimental results_(2)

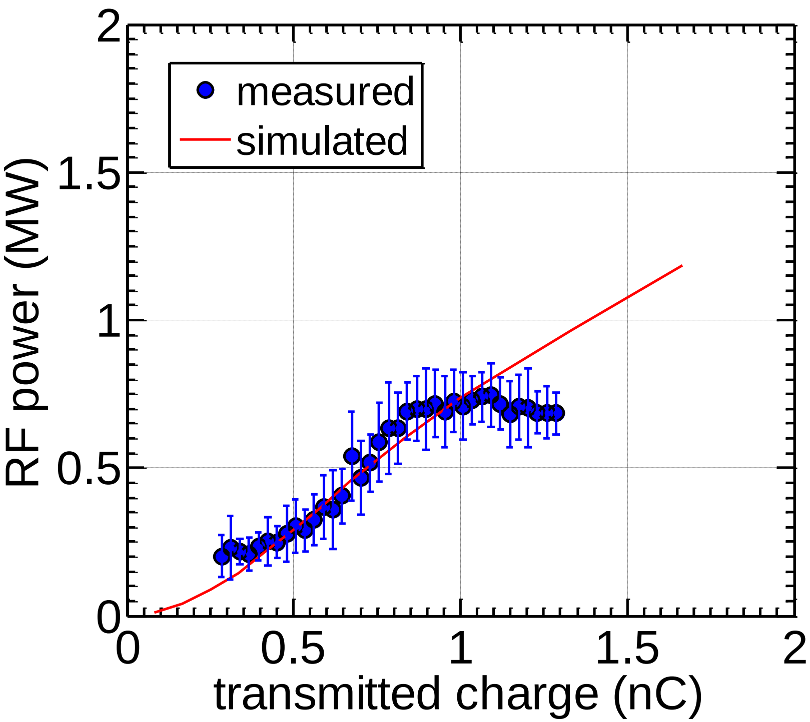


Power vs. drive bunch charge

RF simulation code: CST

Figure out the effective charge, we get good agreement with simulation:

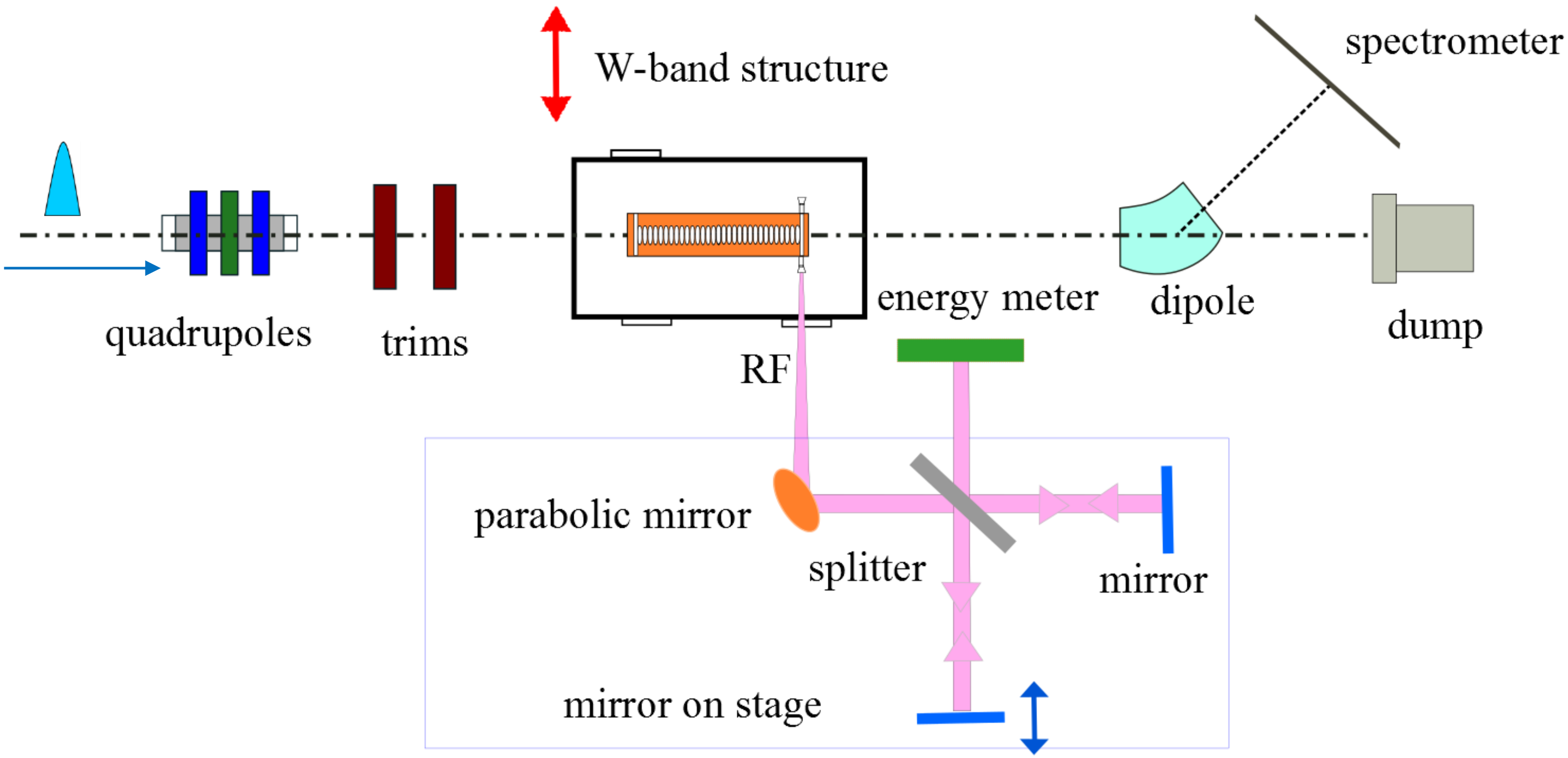
→ $P \propto Q_b^2 \cdot F\,(\sigma_z)^2$



RF frequency measurement set up

Detectors :

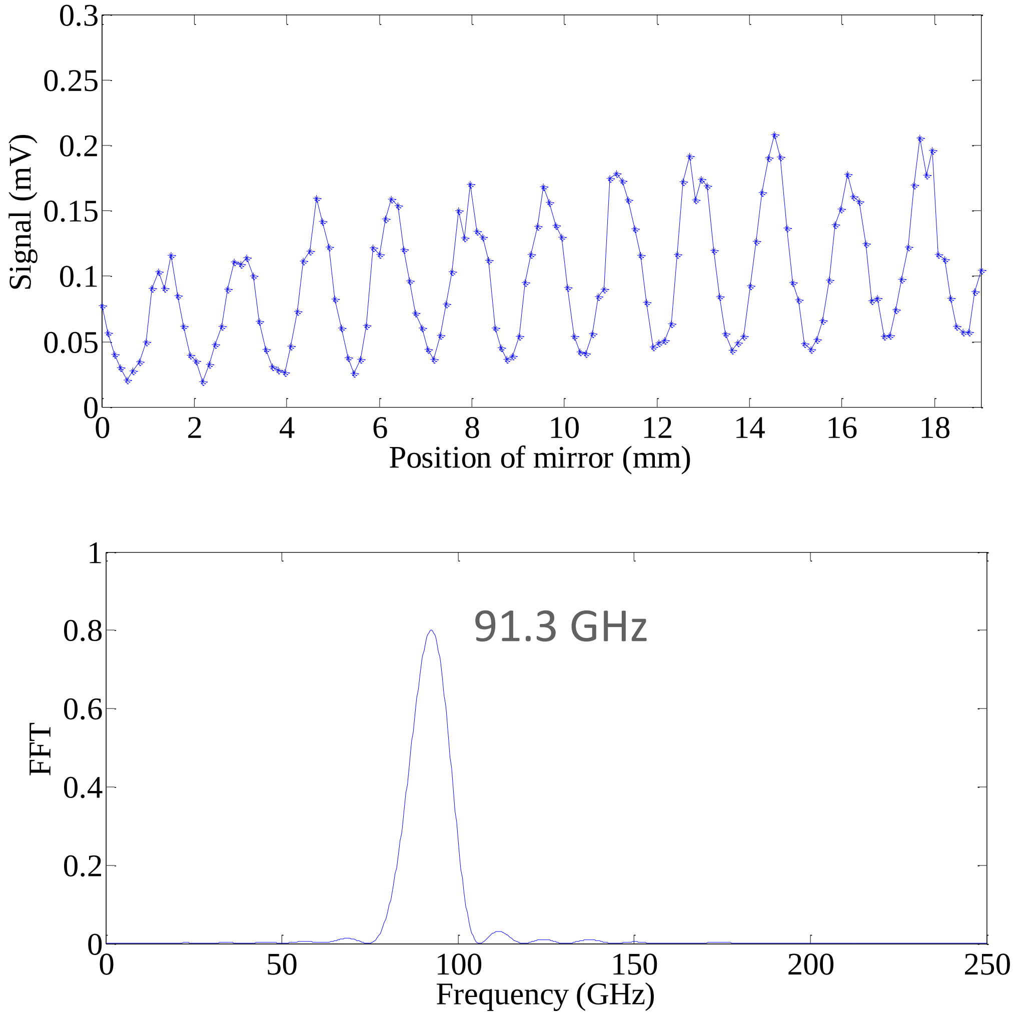
- 1. Energy meter (calibrated): RF output energy
- 2. Spectrometer: energy loss of electron beam
- 3. Michelson interferometer: RF frequency measurement



③ Michelson interferometer

RF frequency measurement results

Frequency measurement of the W-band structure:



Challenges : diagnose the high frequency RF envelope

? No detector to look at the 91 GHz RF pulse directly, currently oscillator (up to 60 GHz at most)

? No easy way to figure out how to alignment the bunch train in right wakefield phase

Highlight : two wakefield interferometry method

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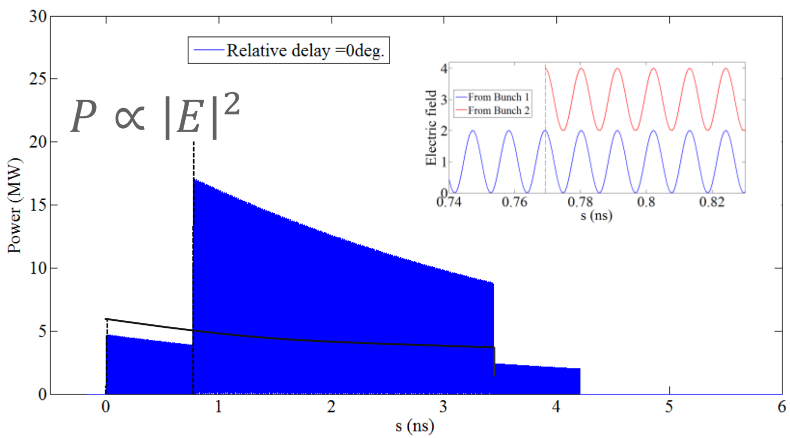
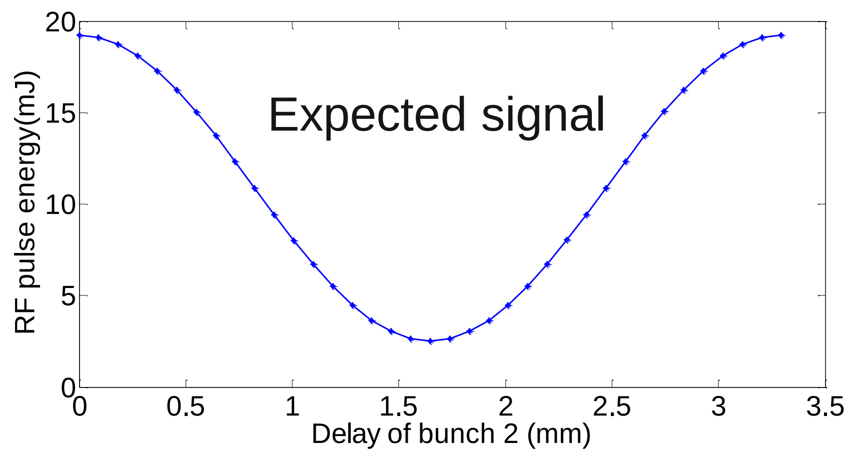
? No easy way to figure out how to alignment the bunch train in right wakefield phase

two wakefield interferometry method :



W-band RF pulse

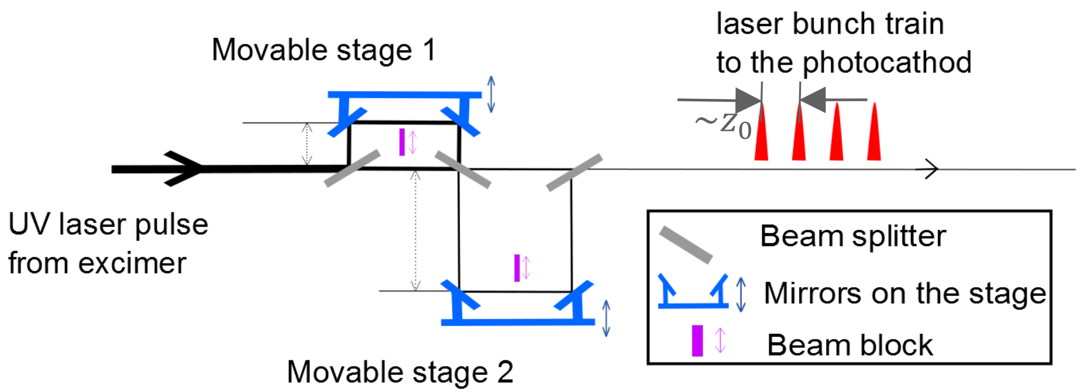


Bunch train experimental set up: laser train

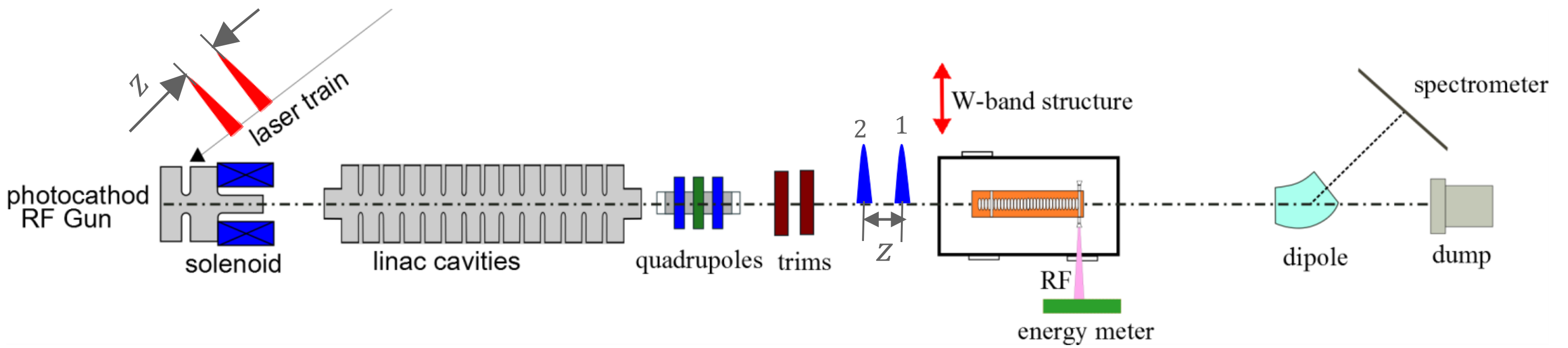
Generation of tunable bunch train:

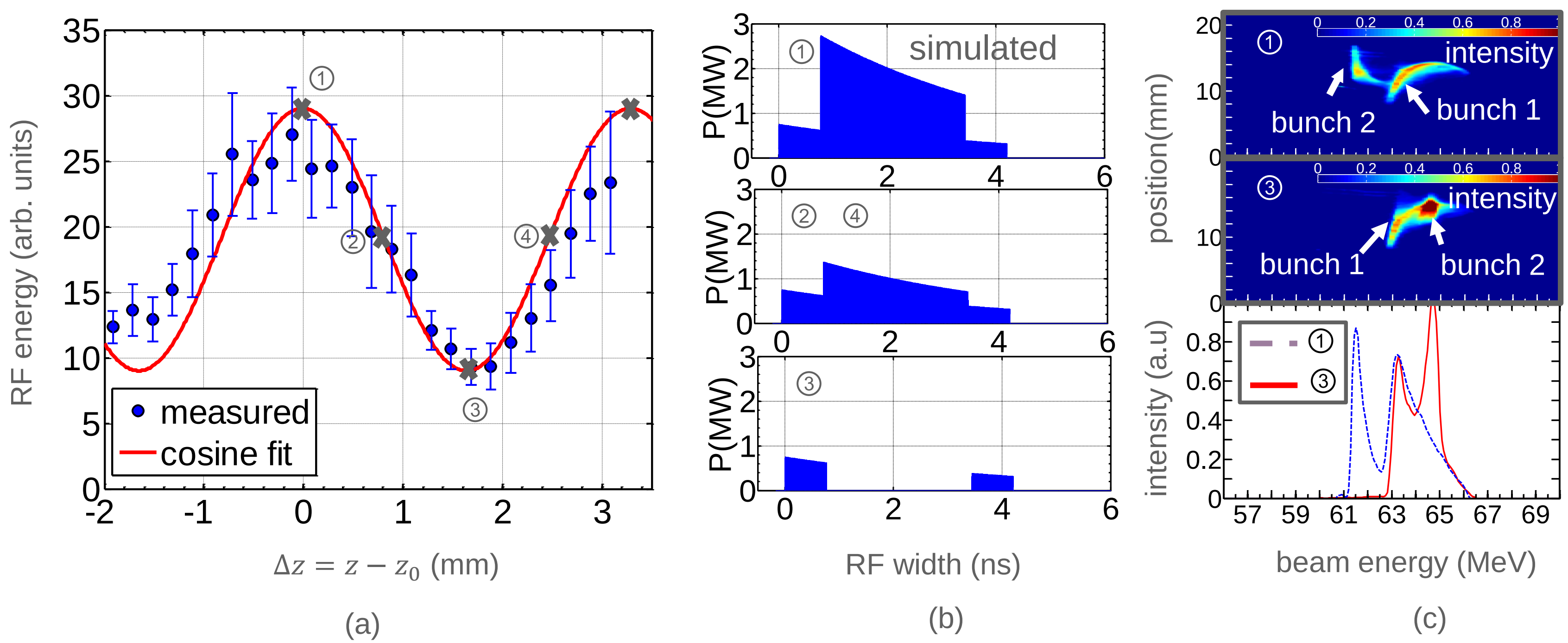
- 1. UV laser slitter
- 2. Movable mirror on stage

Initial interval around : $z_0 = 230\ mm$ (1.3 GHz / 0.769 ns)

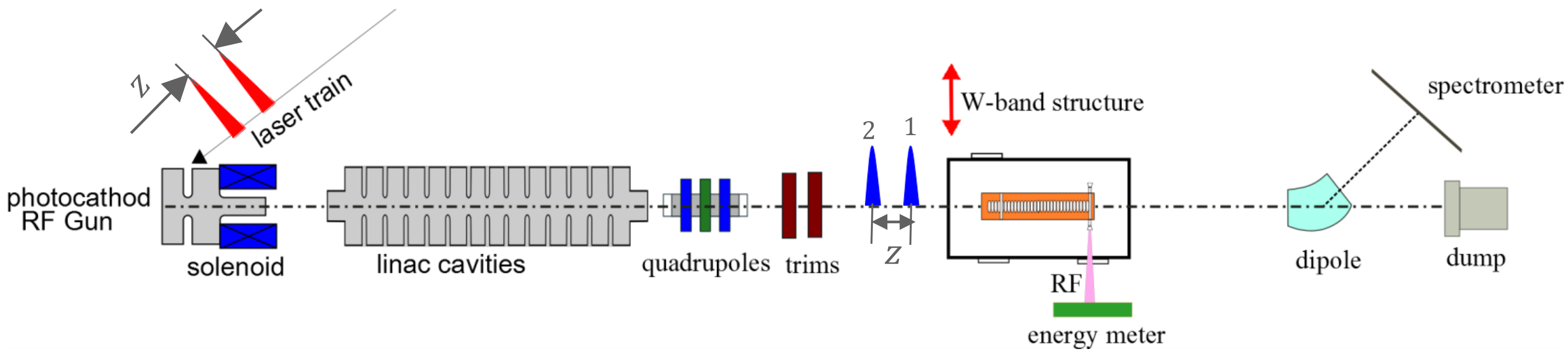


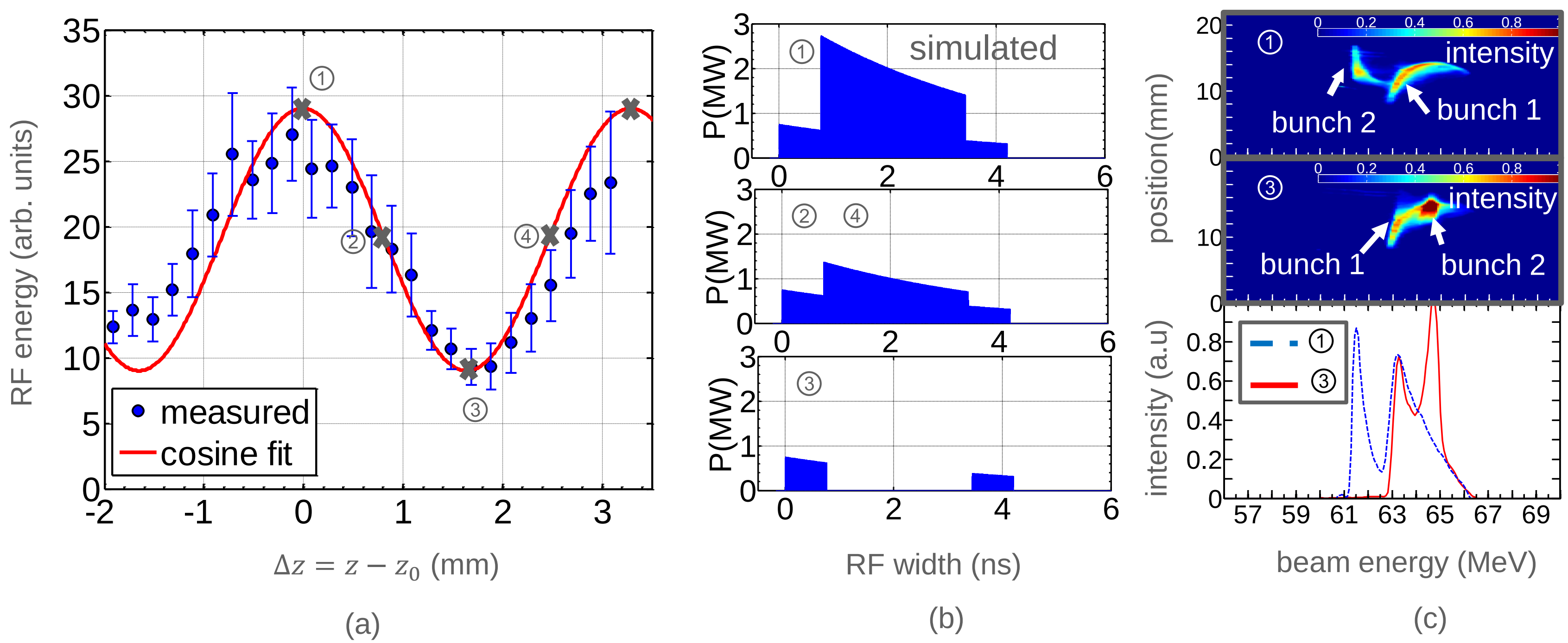
2-bunch train experimental results





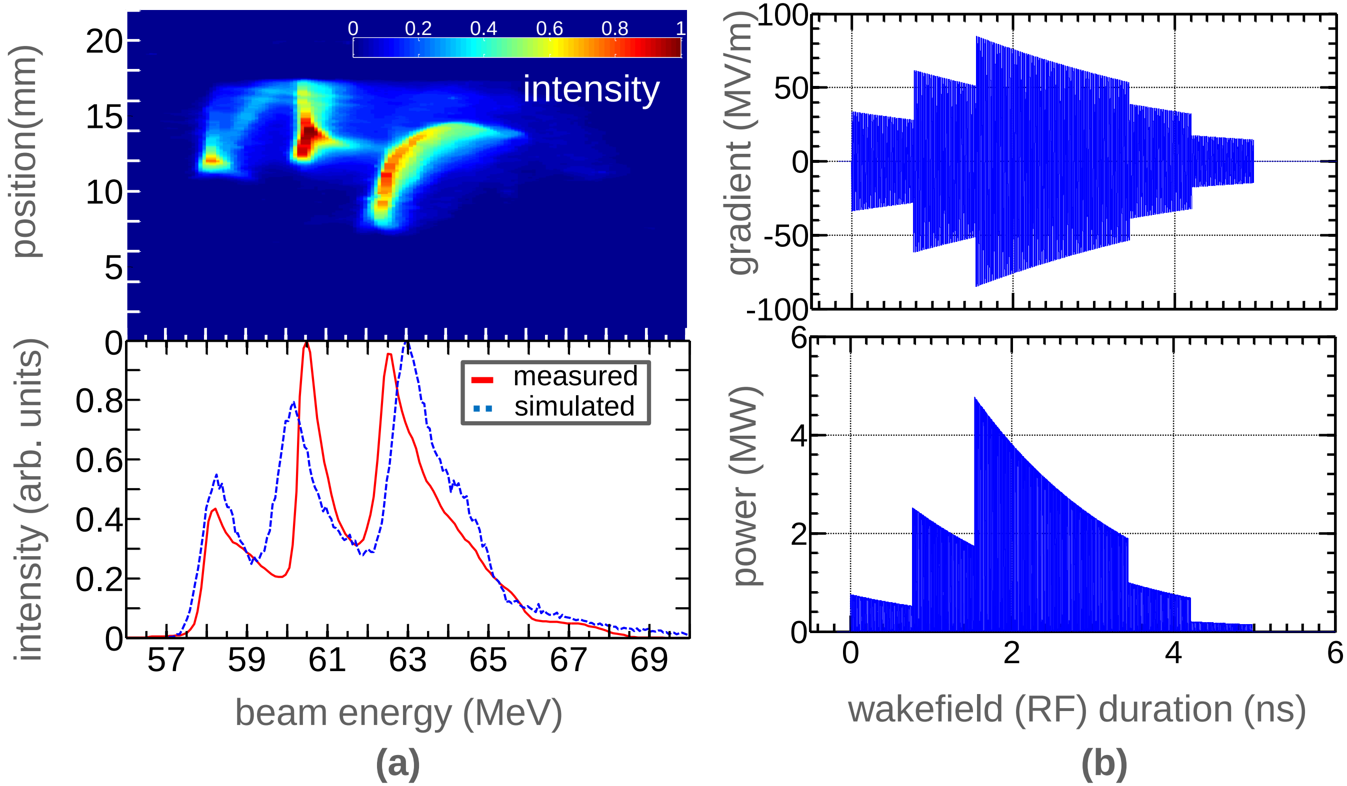
2-bunch train experimental results





sensitivity comparison (other case) : $1\mu J = 1[nC] \cdot 1[keV]$

3-bunch train experimental results



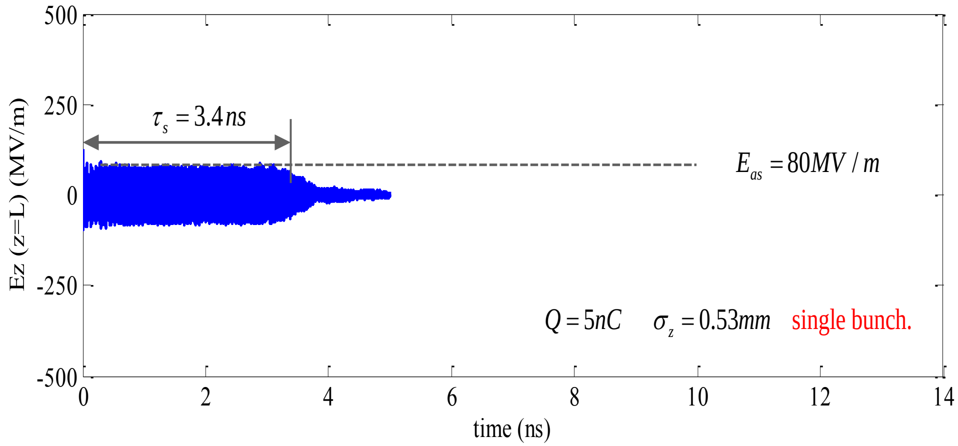
With wakefield interferometry method
→ Precise control of RF phase (bunch1~3 loss energy of :1.3 MeV, 3.2 MeV, 4.4MeV)
→ Generate maximum RF power

Derived wakefield gradient
$E_{peak} = 85\ MV/m$ (high gradient)

Derived output RF pulse:
$P_{peak} = 5\ MW$ (high power)

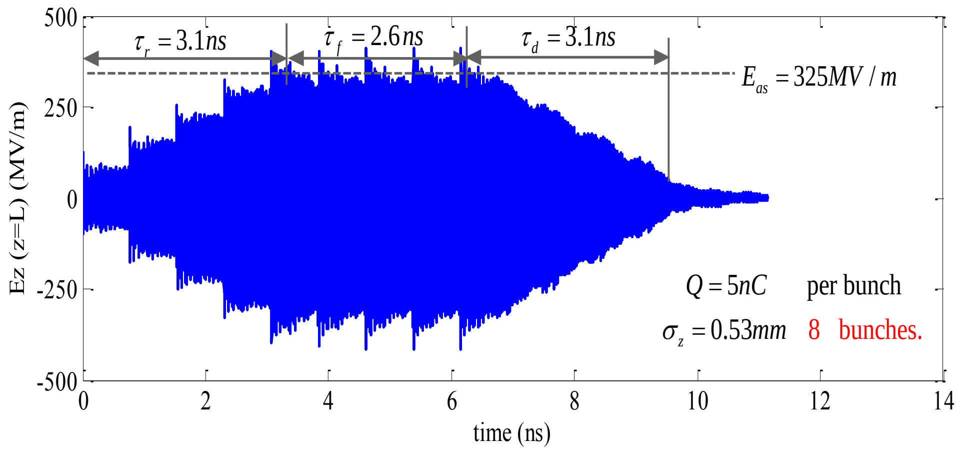
Plan: increase the power and gradient

With structure attenuation coefficient α: $E_t = NE_s\left((1-e^{-\alpha L})\ /\ \alpha L\right)$



RF peak power :

p_S = 4.2 [MW]



RF peak power :

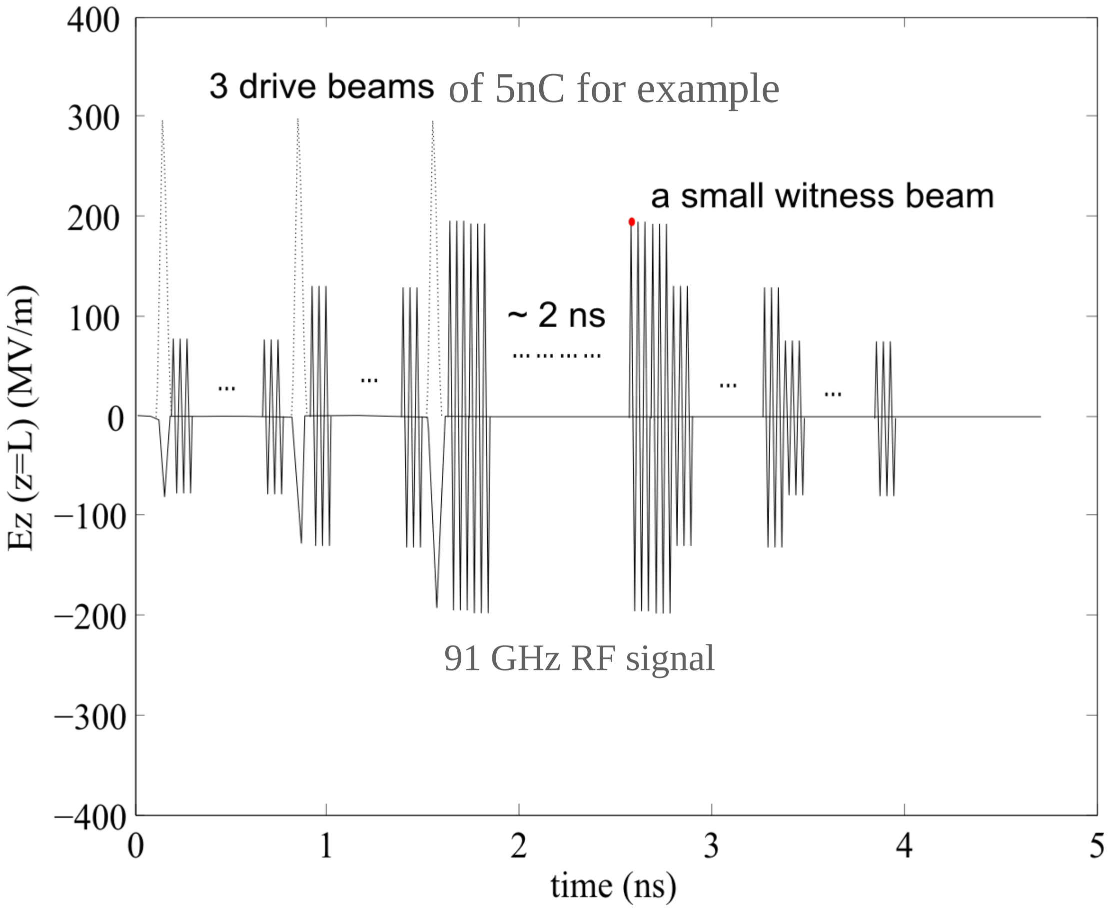
p_t = 69.6 [MW]

For 10 nC bunch train:

E_t = 400 [MV/m]
p_t = 105.6 [MW]

Results from CST simulation

Plan: accelerate the witness beam to higher energy



Energy gain of witness beam ~ 20 MeV after the structure (~0.12 m)

Summary

1. We measured 5 MW RF @ 91.3 GHz, wakefield gradient is 85 MV/m. The W-band structure turns out to be a high power RF generator & also compact /advanced accelerator of high gradient

2. The newly-developed two-beam wakefield interferometry method is an effective diagnostic for wakefield, which benefits the precise RF phase control in advanced wakefield accelerators.

3. We plan on the 100 MW & 400 MV/m in the W-band structure in future (promising)

Acknowledgement

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- P. Piot from FNAL

Thanks for your attention

Back up

Method: parameter of the PETS

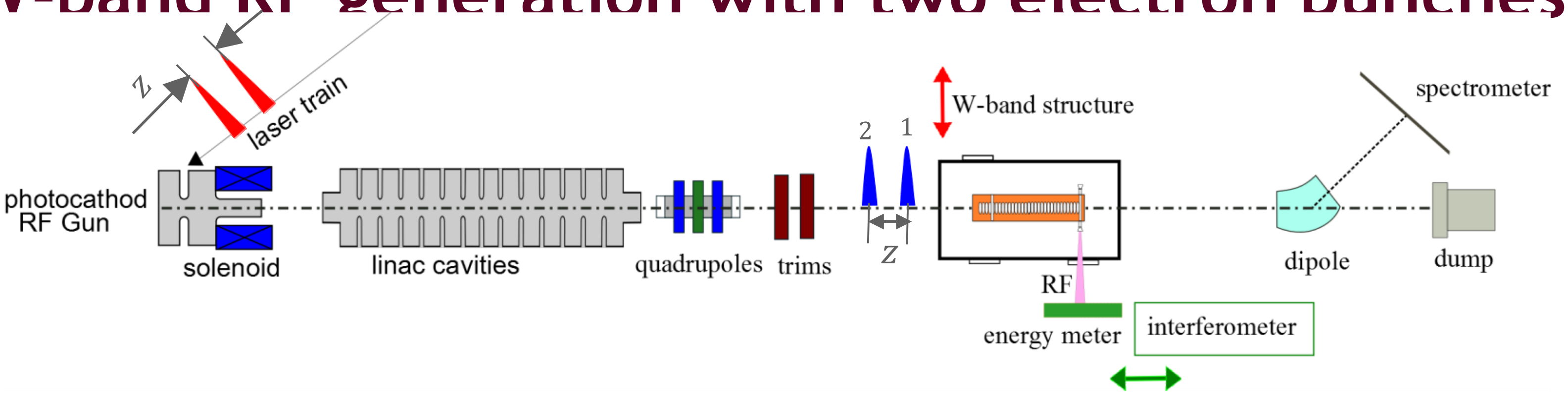
Table. parameters of the W-band PETS

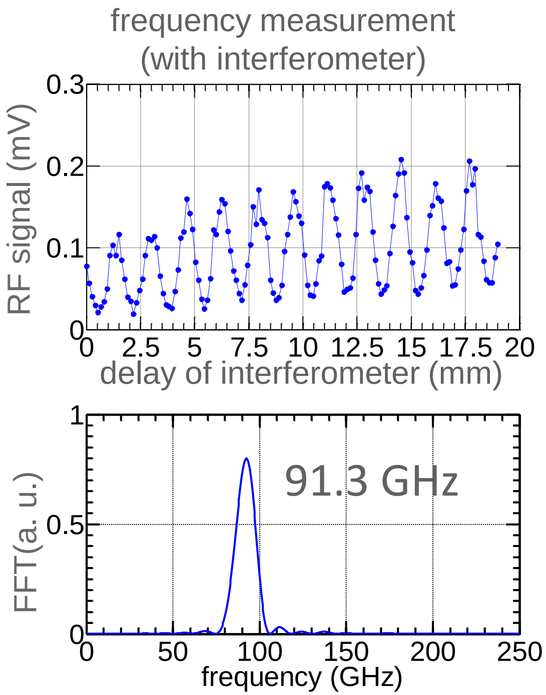
RF frequency*	f_0	88.0 ~ 94.0 GHz
The aperture between the two plates	2a	0.80 ~ 1.20 mm
Period length	z_p	1.10 mm
Half length of the groove in y direction	y_{max}	1.25 mm
Depth of the groove	x_{max}	0.90 mm
Total length of the structure	L	123.20 mm
Relativistic group velocity	β_g	0.105 #
Total quality factor	Q	2560 #
"R over Q" per unit length	R/Q	83.3 kΩ/m #
Loss factor per unit	k_L	$1.33 \times 10^{16} V/(C \cdot m)$ #

*Frequency f_0 can be tuned by adjusting gap 2a

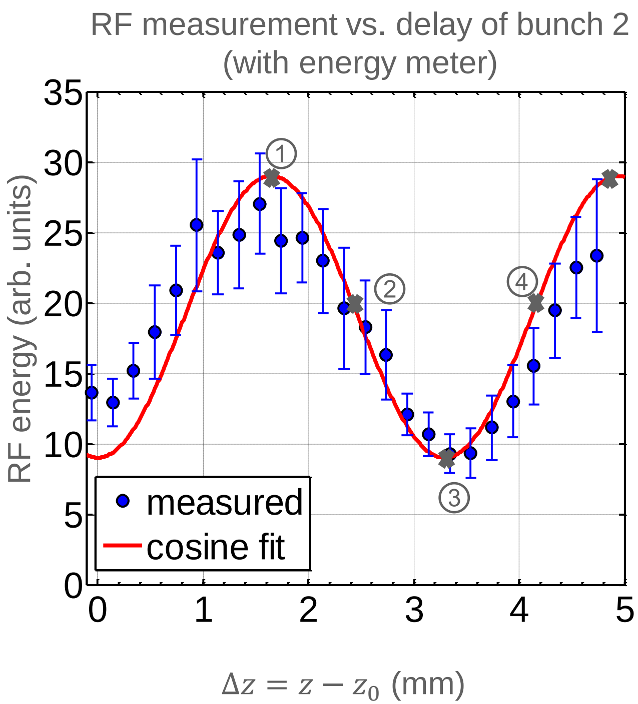
Value at f_0 = 91 GHz

W-band RF generation with two electron bunches

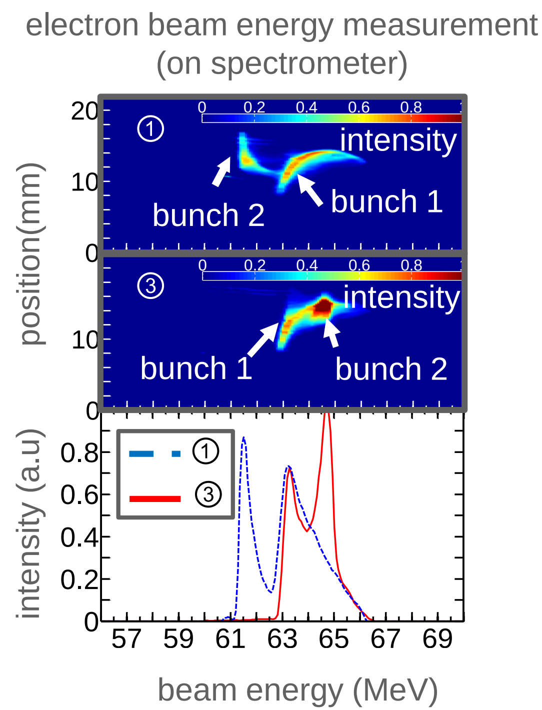




(a)



(b)



(c)