

# Impact of beam loading on the breakdown rate

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for the Dogleg team

# Outline

- Breakdown limitations for CLIC
- Experimental setup
- Measurement points
- Results
- Future developments

# Breakdown limitations for CLIC

**Strong accelerating fields**  
(~100 MV/m)



**Vacuum arcs are an issue**

## CLIC CDR LIMIT:

Max BD rate allowed  
 $3 \times 10^{-7}$  BD pulse<sup>-1</sup> m<sup>-1</sup>

To contain **peak**  
**luminosity** loss < 1%

## BREAKDOWN EFFECT:

- Loss of acceleration
- Beam kicks
- Structure damage
- Activation
- ...

## BDR SCALING LAW

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

$\tau$  = pulse length  
E = Accelerating field

# Motivation

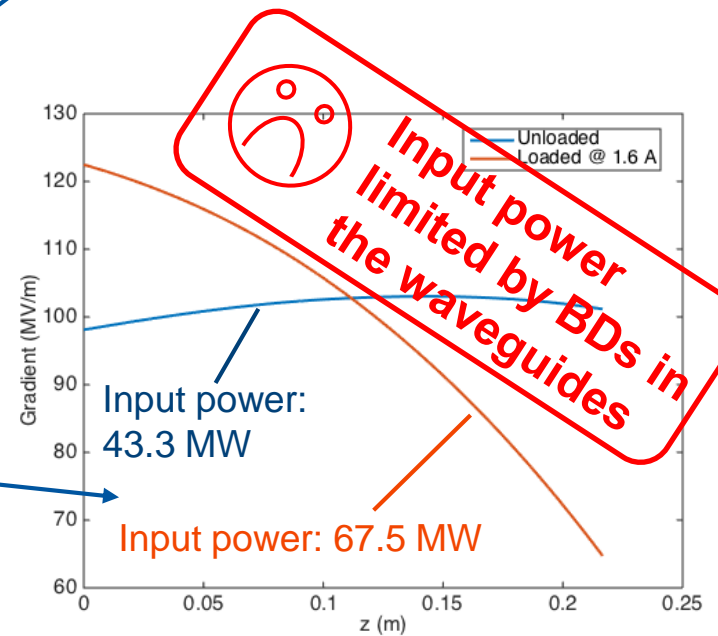
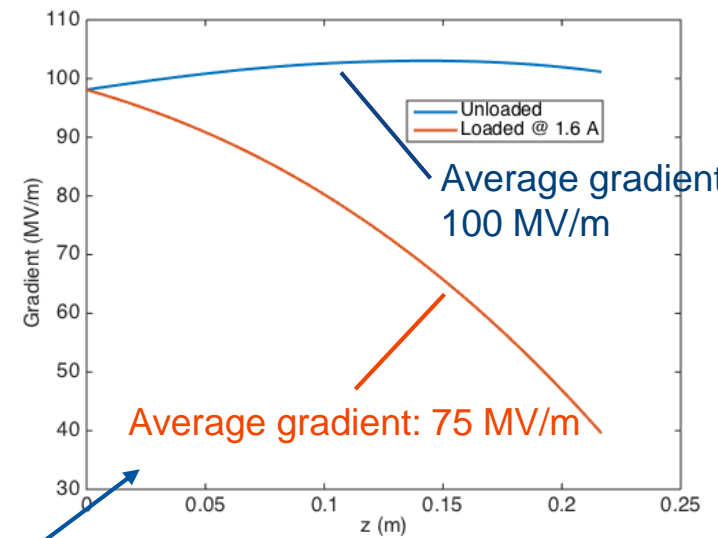
The internal field profile is modified by the presence of the beam

Consequently, the beam energy gain will be lower:

$$\Delta W = q \cdot \int_0^L E_{acc}(z) dz = q \cdot \langle E_{acc} \rangle \cdot L$$

## Possible measurements:

- Fixed input power
- Fixed average gradient
- Decelerating the beam



Loaded gradients @ 1.6 A beam current

# Motivation

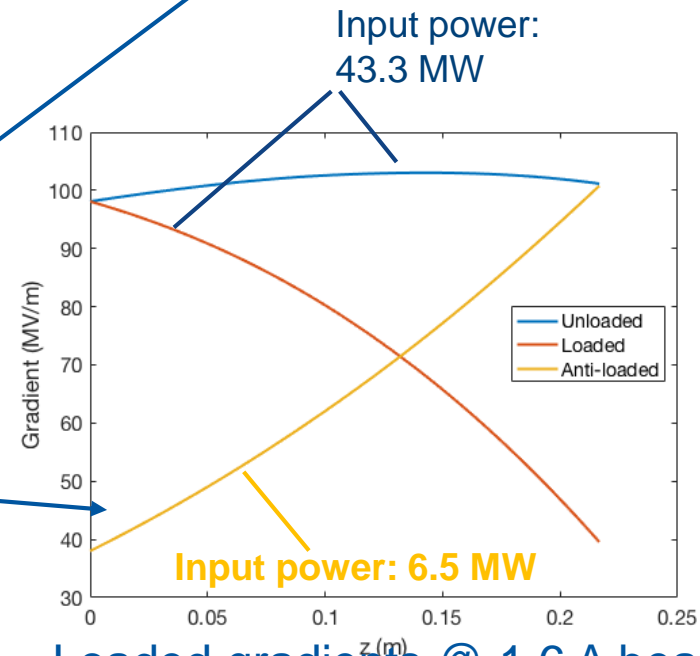
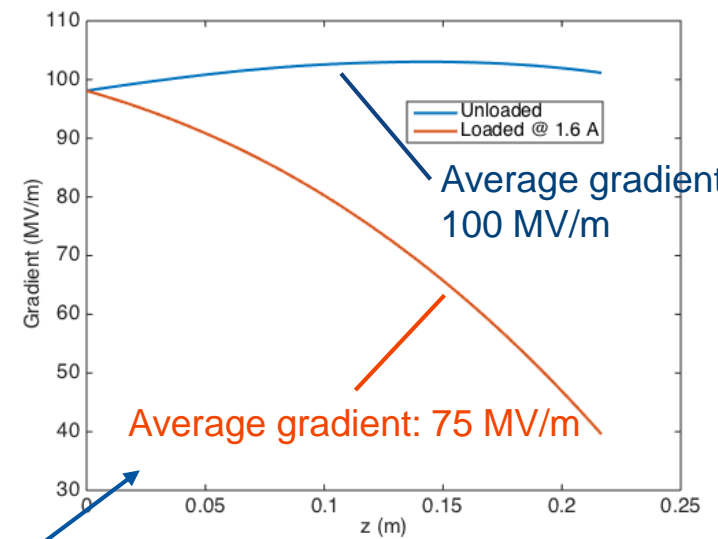
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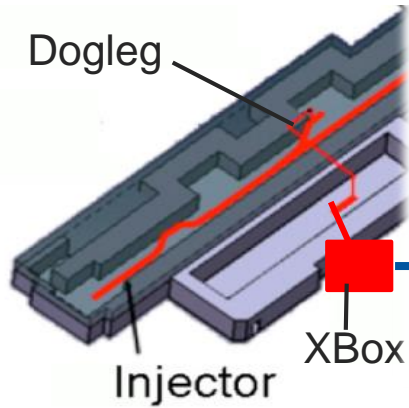
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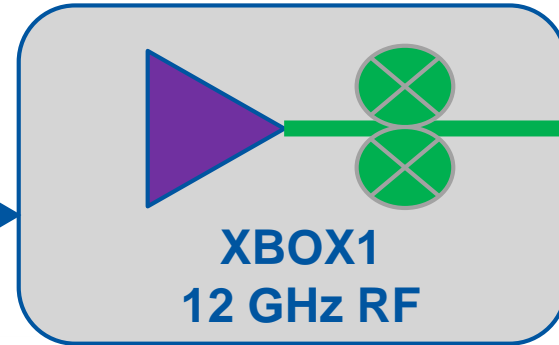
Loaded gradients @ 1.6 A beam current

# Experiment layout



## 12 GHz RF:

- ✓ 90 MW RF power
- ✓ Up to 50 Hz rep. rate



## Beam:

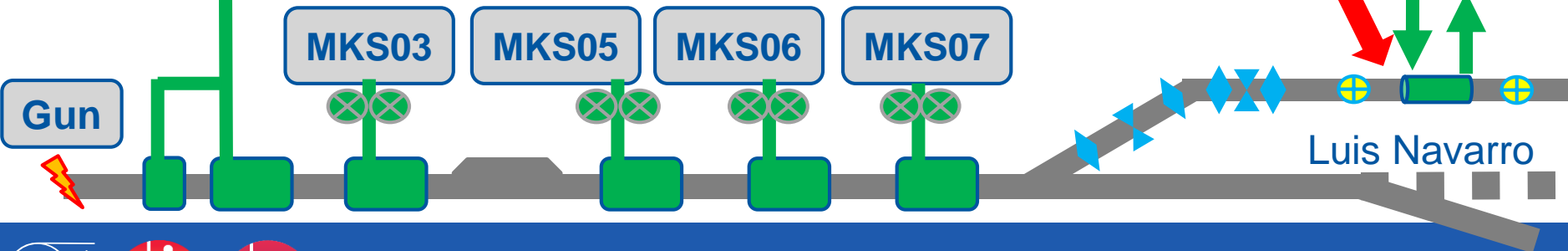
- ✓ CTF3 Drive Beam modified
- ✓ 3 GHz beam at ~1.6 A
- ✓ Pulse length up to 250 ns
- ✓ Energy ~125 MeV at structure
- ✓ Up to 25 Hz pulse rep. rate



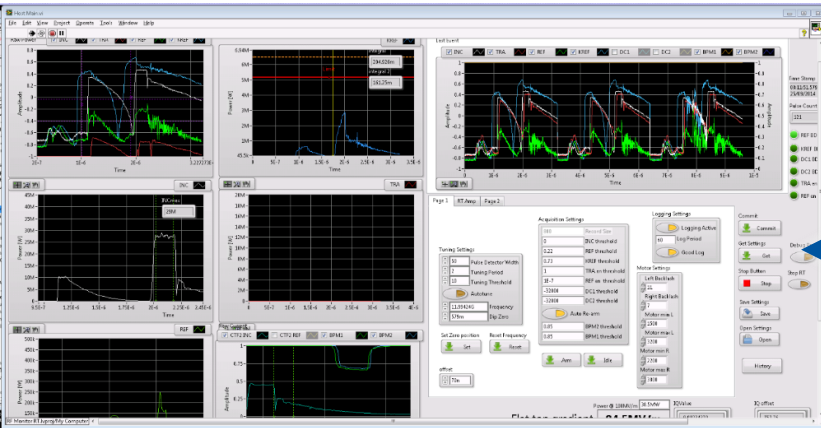
## Structure (TD26CC):

- Tapered
- Damped
- Compact Couplers

35 m low loss waveguide

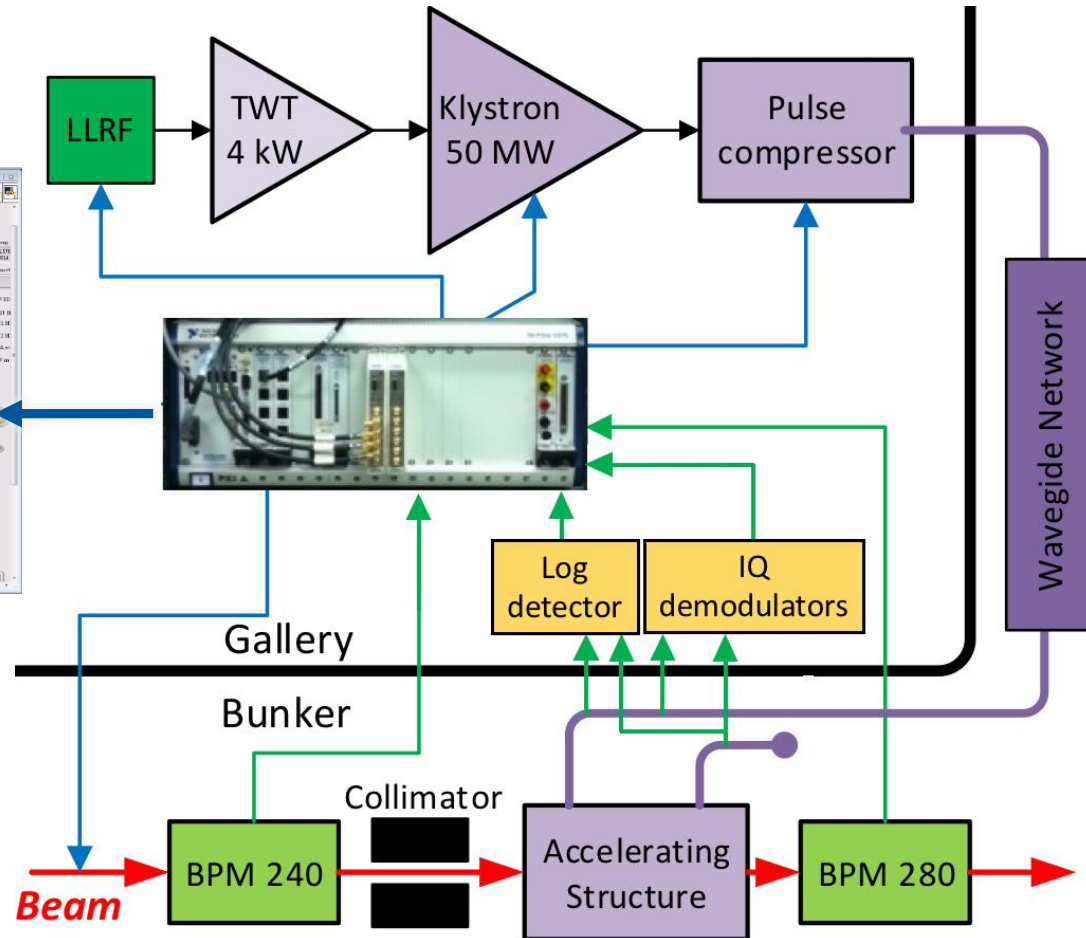


# DAQ and Control system



## PXI NI unit:

- Real time interlocking
- Data taking and storage
- 12 GHz RF control from LLRF
- User interfaced with Labview



# Breakdown detection

Beam presence complicates everything

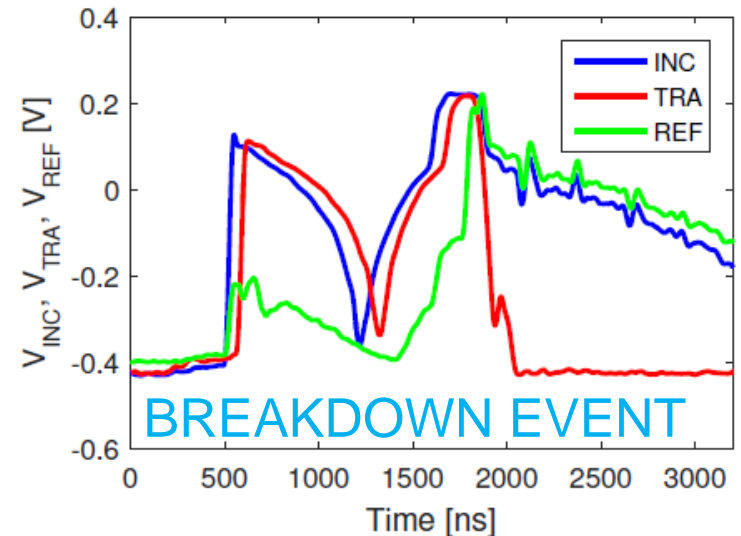
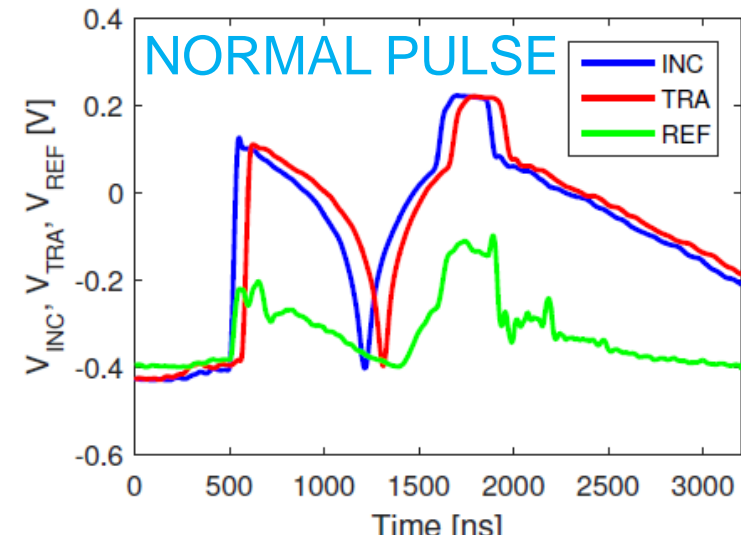
- Faraday cups would occlude the beam pipe
- External radiation monitors are blind
- We can just rely on **RF signals**

The plasma is charged and reflects the RF arriving after the breakdown



REFLECTED POWER SIGNAL

TRANSMITTED POWER SIGNAL



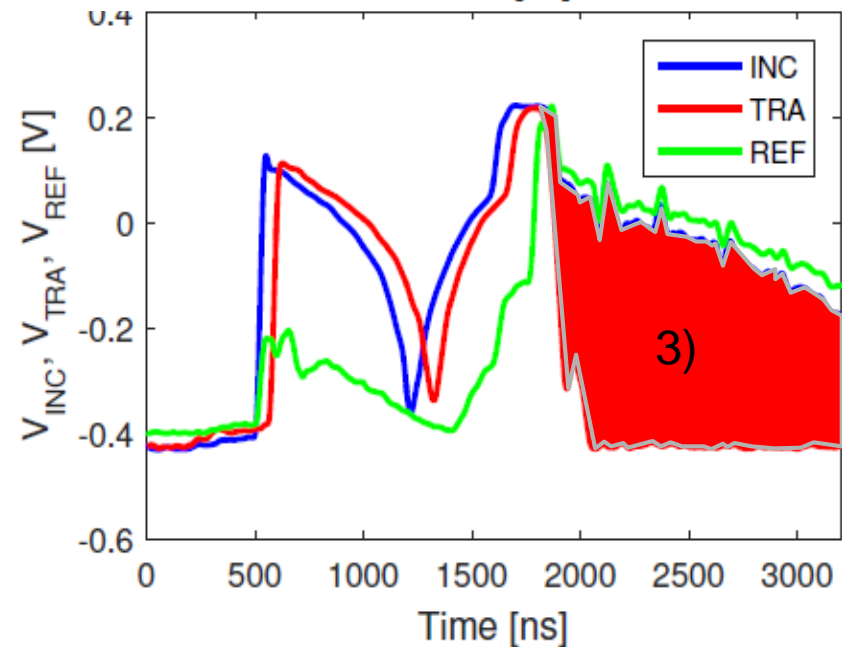
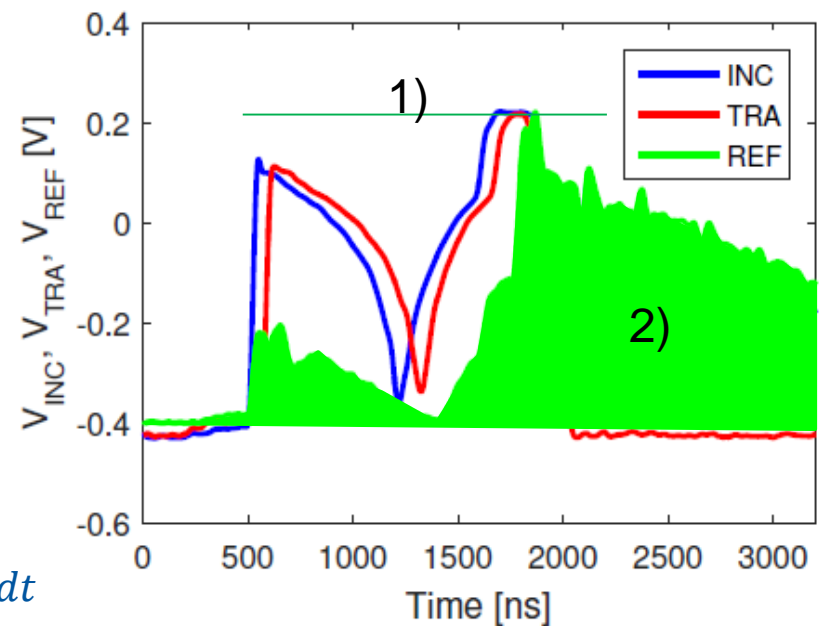
# Online triggers

3 triggers are used to **interlock** the machine:

- 1) Peak Reflected Power  $\max(\text{REF})$
- 2) Reflected Energy  $\int \text{REF}(t)dt$
- 3) Missing Transmitted Energy  $\int (\text{INC}(t) - \text{TRA}(t))dt$

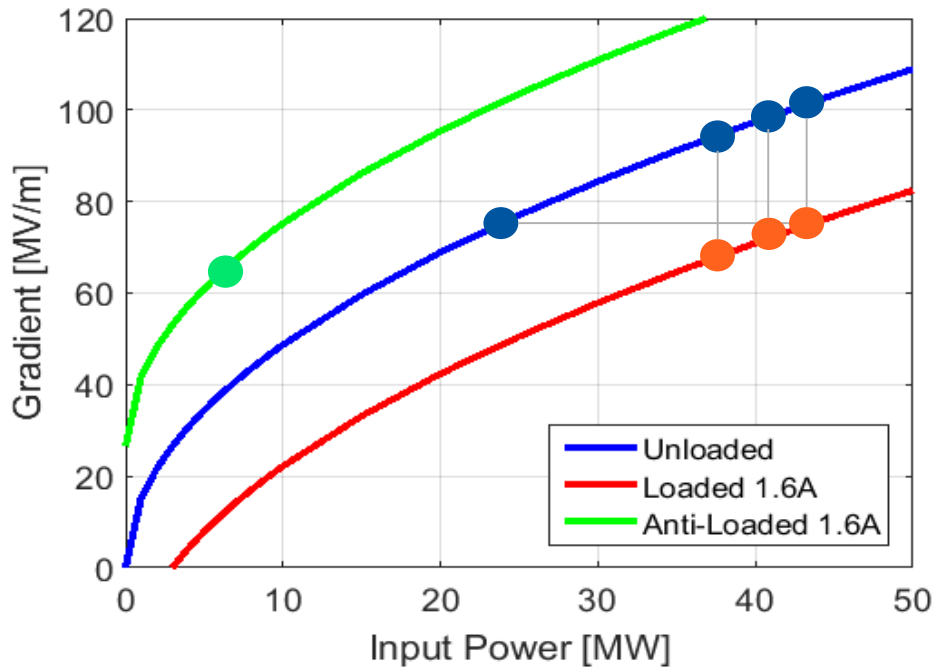
Using log-detectors, Interlocks (2) and (3) offer a good distinction between breakdowns and normal events.

**Redundancy** is a key feature in order not to miss any breakdown



Jorge Giner-Navarro

# Measurement points



During 2016:

- Over 30 weekends of **runs with beam**
- Running **without beam** during the week

Accessible **input power** measurements:

↑ Higher: limited by BDs in WGs ☹️

- 43.3 MW
- 41 MW
- 38 MW



↓ Lower: limited by run time ☹️

Measurements **for comparison**:

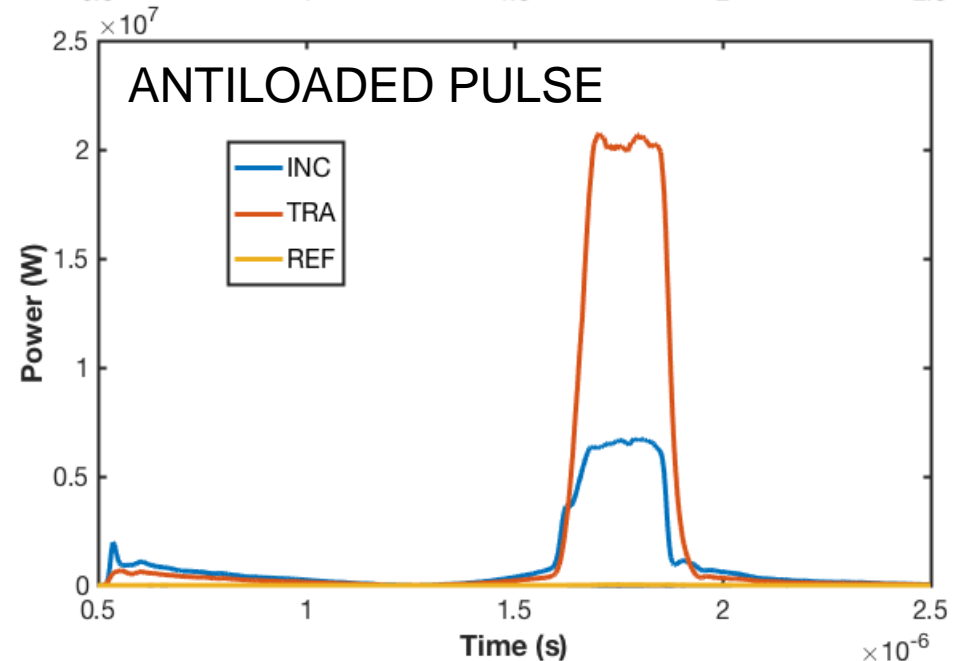
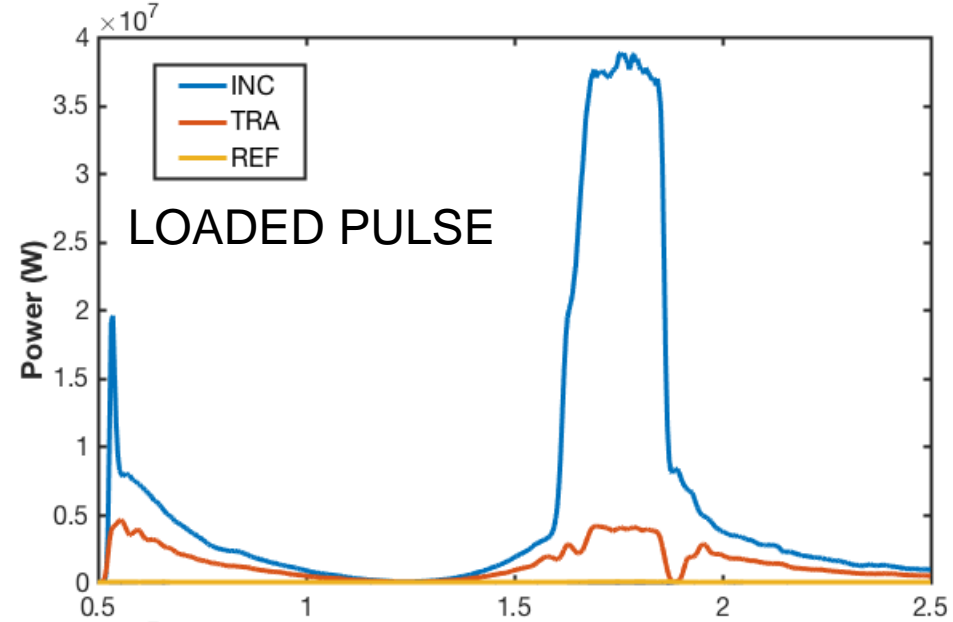
- Same input power      Unloaded - Loaded
- Same average gradient      Unloaded - Loaded
- Same output gradient      Unloaded - Antiloading

# Beam-Loading

**Goal:** maximize the beam effect.  
Higher beam current than CLIC specifications

$$I_{\text{BEAM}} = 1.6 \text{ A}$$

- **CLIC nominal RF pulse:**  
70 ns rising (filling) time +  
180 ns flat-top
- **Beam pulse length** set longer than the flat-top, to avoid exceeding flat-top power level
- In **anti-loaded case**, beam set also at the beginning of the rise of the compressed pulse

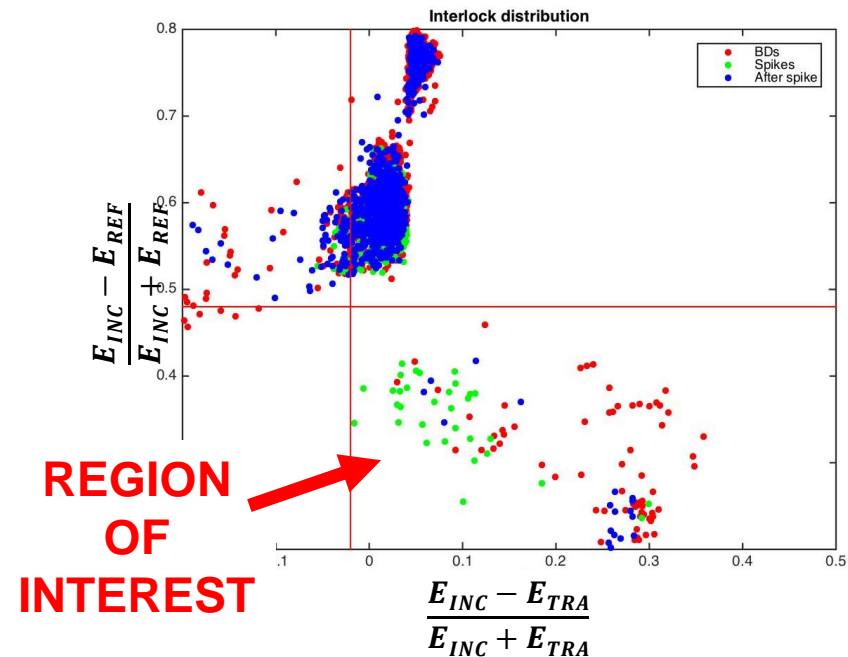
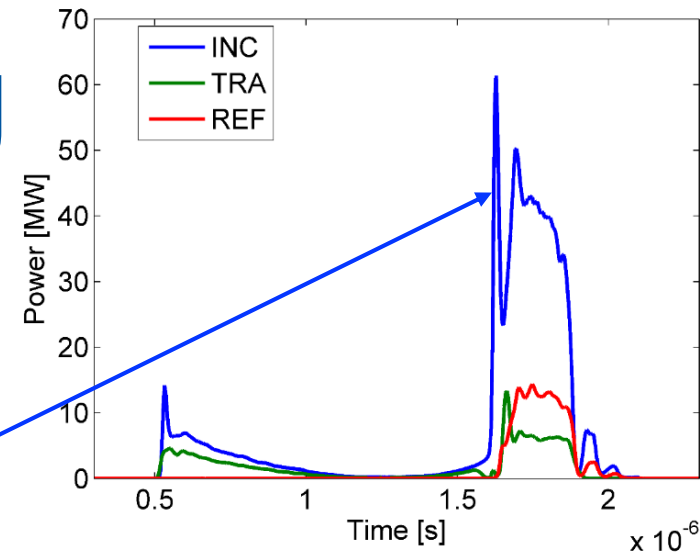


# Breakdown counting

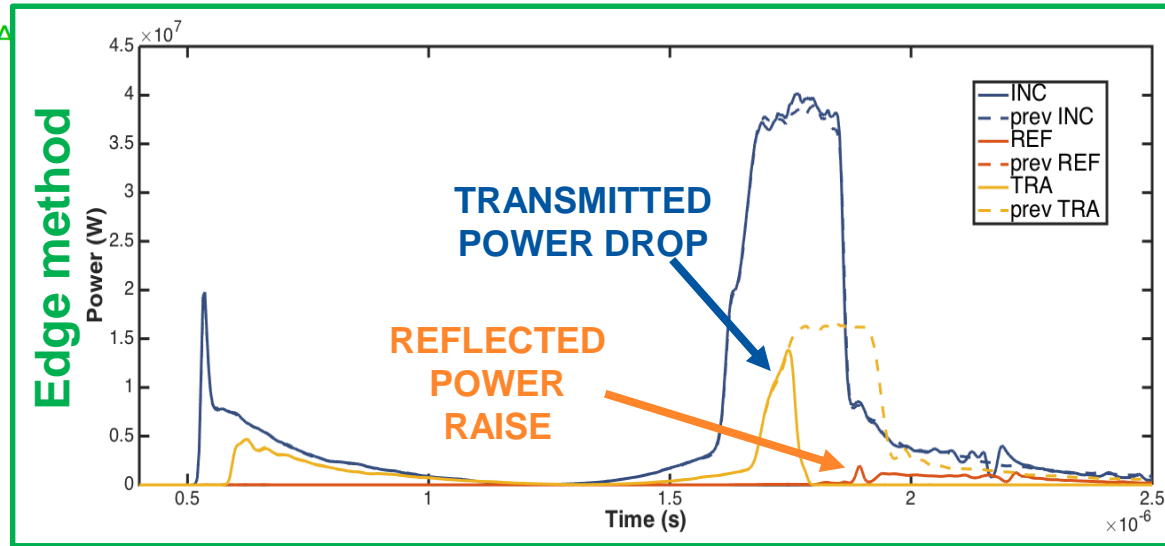
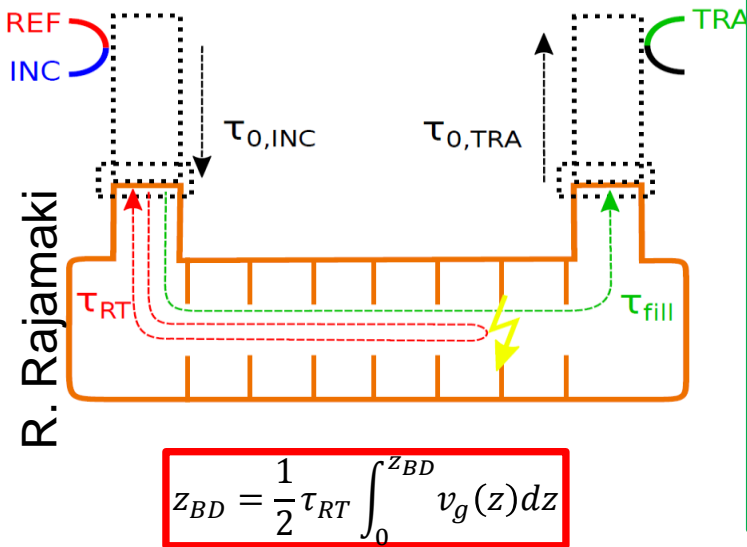
- Filter out all the **breakdowns outside the structure** (Pulse compressor, waveguides, fake interlocks, ...)
- Filter out all the BDs induced **power spikes**
- Filter out BDs triggered after a spike

In addition, for runs with beam

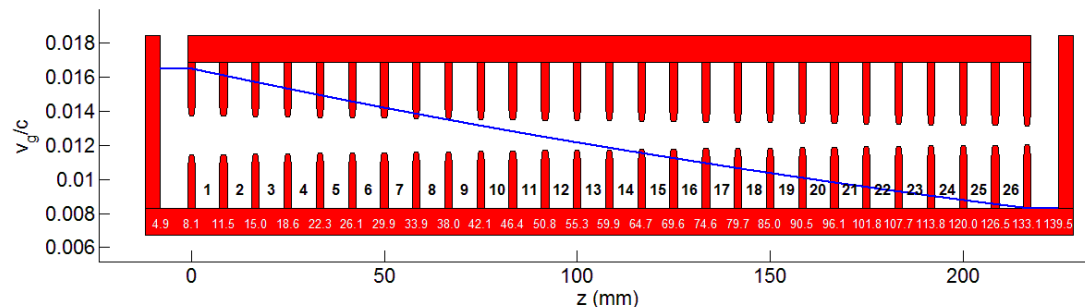
- Filter out BDs **without beam**
- Filter out BDs triggered immediately after another BD without beam



# Positioning methods



- Positioning done using the **time delays** of the signals
- **Spatial position** deduced since **group velocity profile** is known



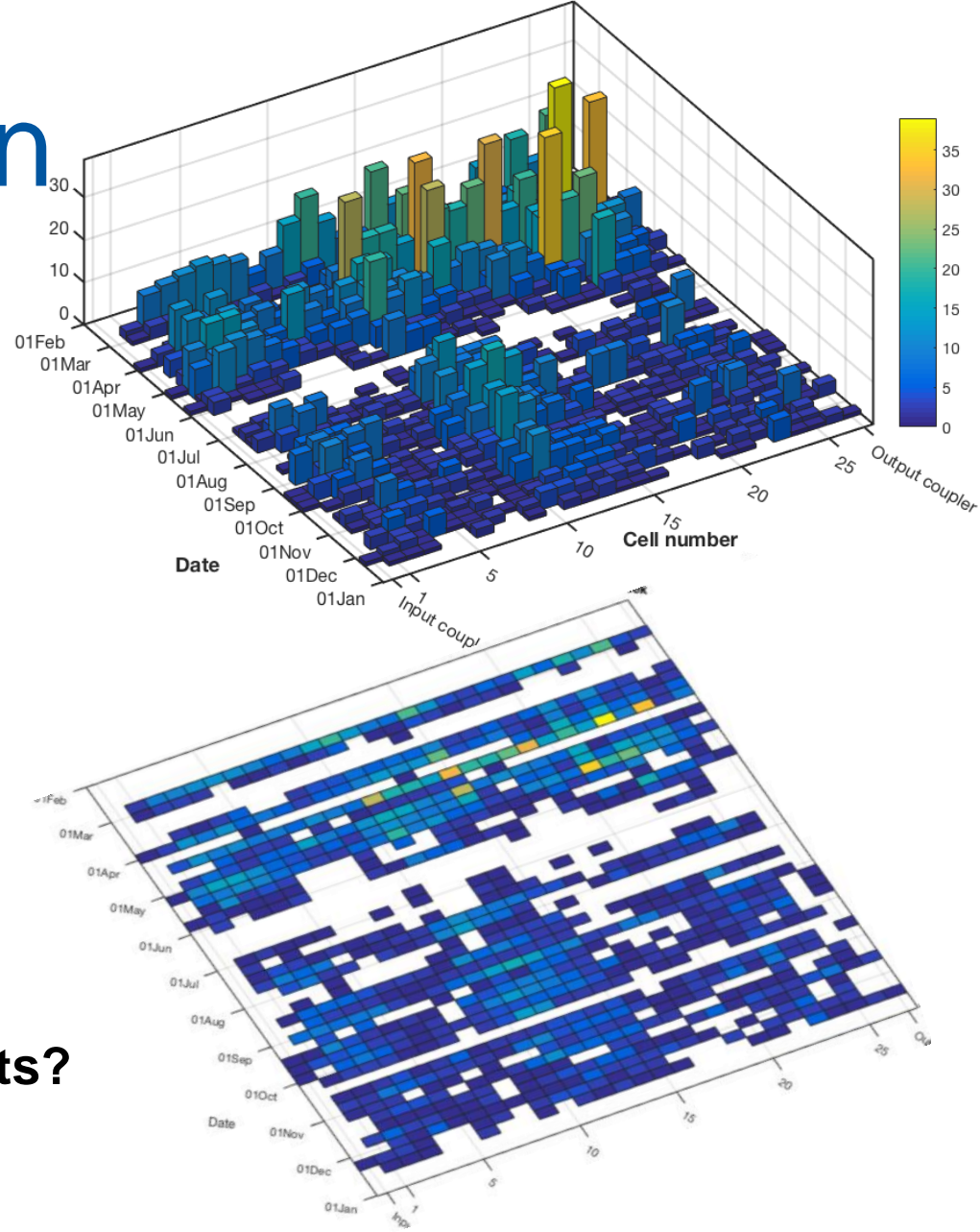
# 2016 campaign

During 2016 collected 313 Mpulses

- 12 Unloaded runs @ 43.3 MW input power
- 7 Unloaded runs @ 41 MW input power
- 13 Unloaded runs @ 38 MW input power
- 2 Unloaded runs @ 24.6 MW input power
- 12 Loaded runs @ 43.3 MW input power
- 3 Loaded runs @ 41 MW input power
- 16 Loaded runs @ 38 MW input power
- 4 Antiloading runs @ 6.5 MW input power

The **behavior of the breakdown distribution** is not clear:

- Switched many times between **different input powers** and **loaded/unloaded regime impacts?**





# Beam effect on BD position

- Different **gradient profile** when the **beam** is in the cavity

- Overall it's known that

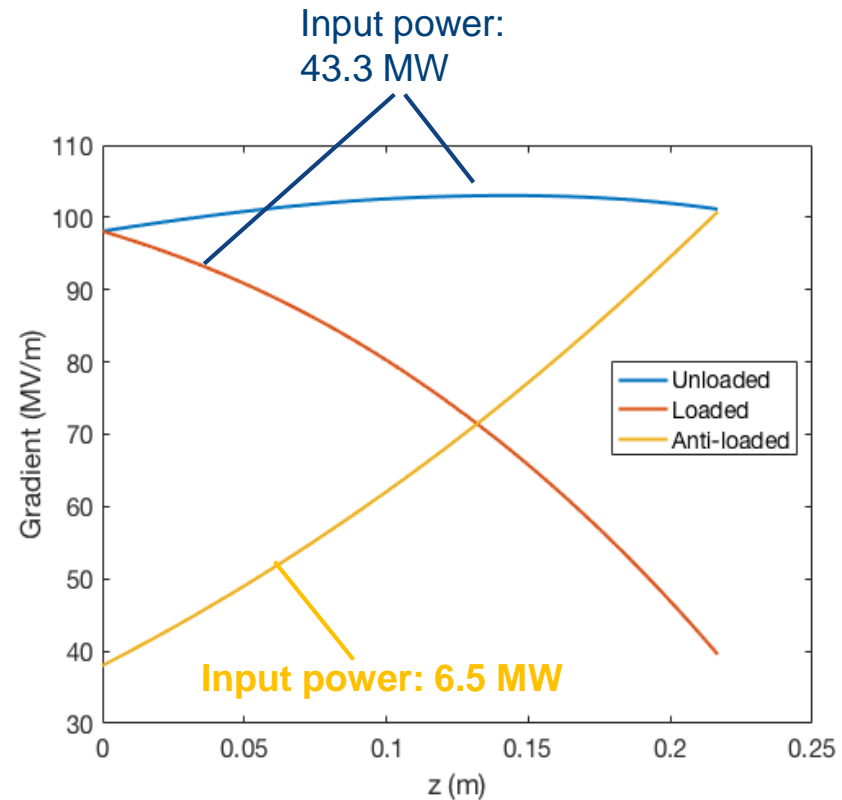
$$BDR \propto E^{30} \tau^5$$



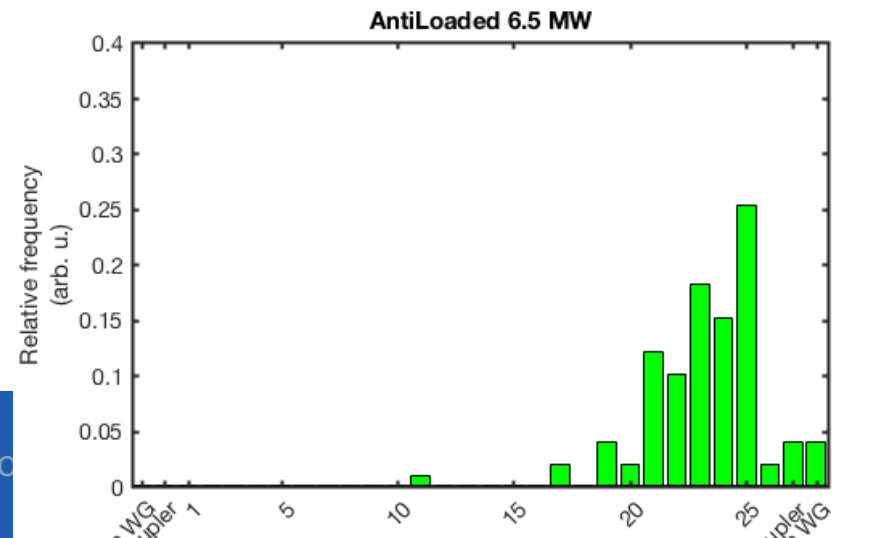
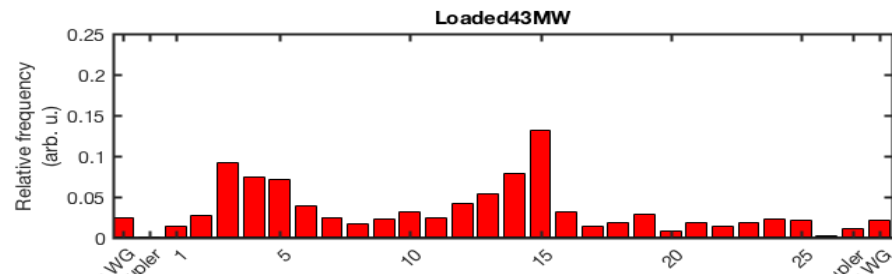
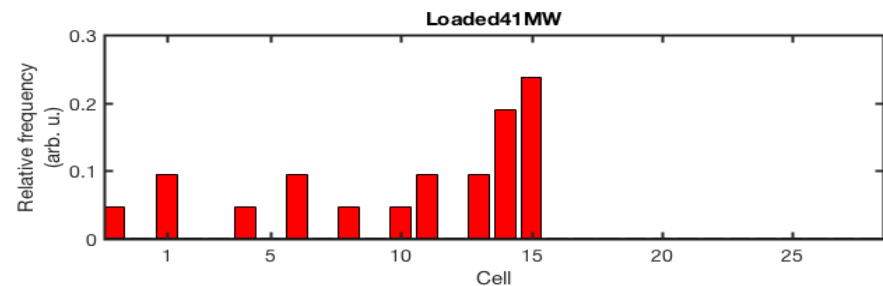
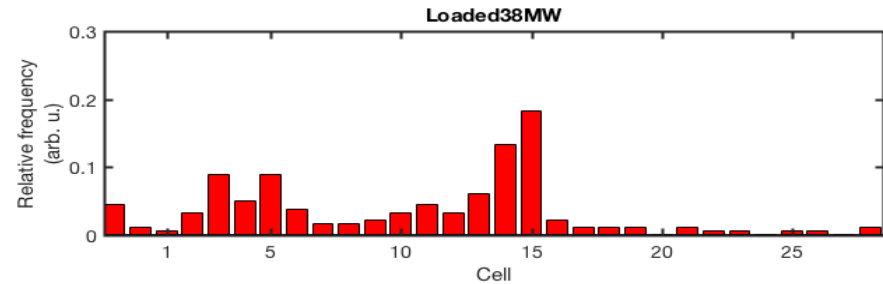
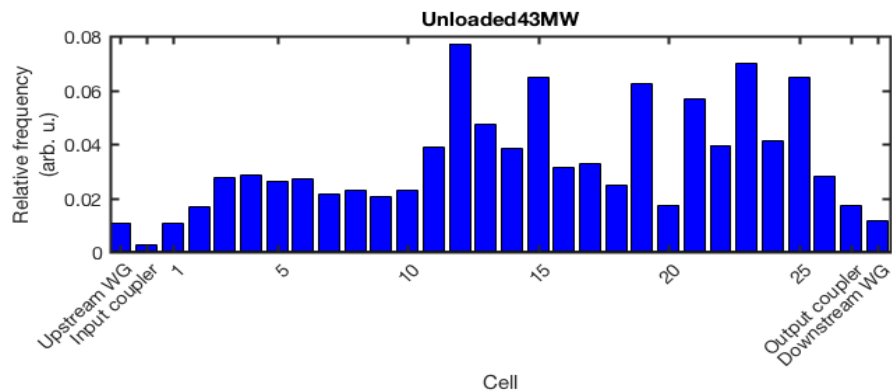
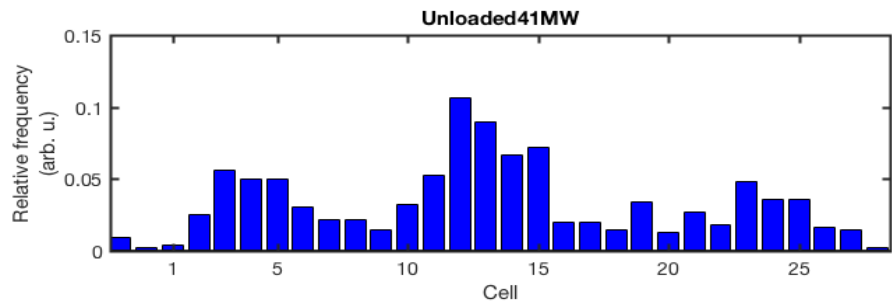
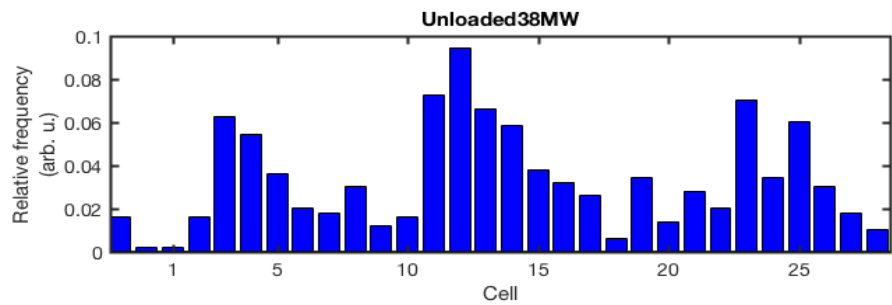
**One would expect more BDs where the field is higher**

- Following the same logic, in every cell

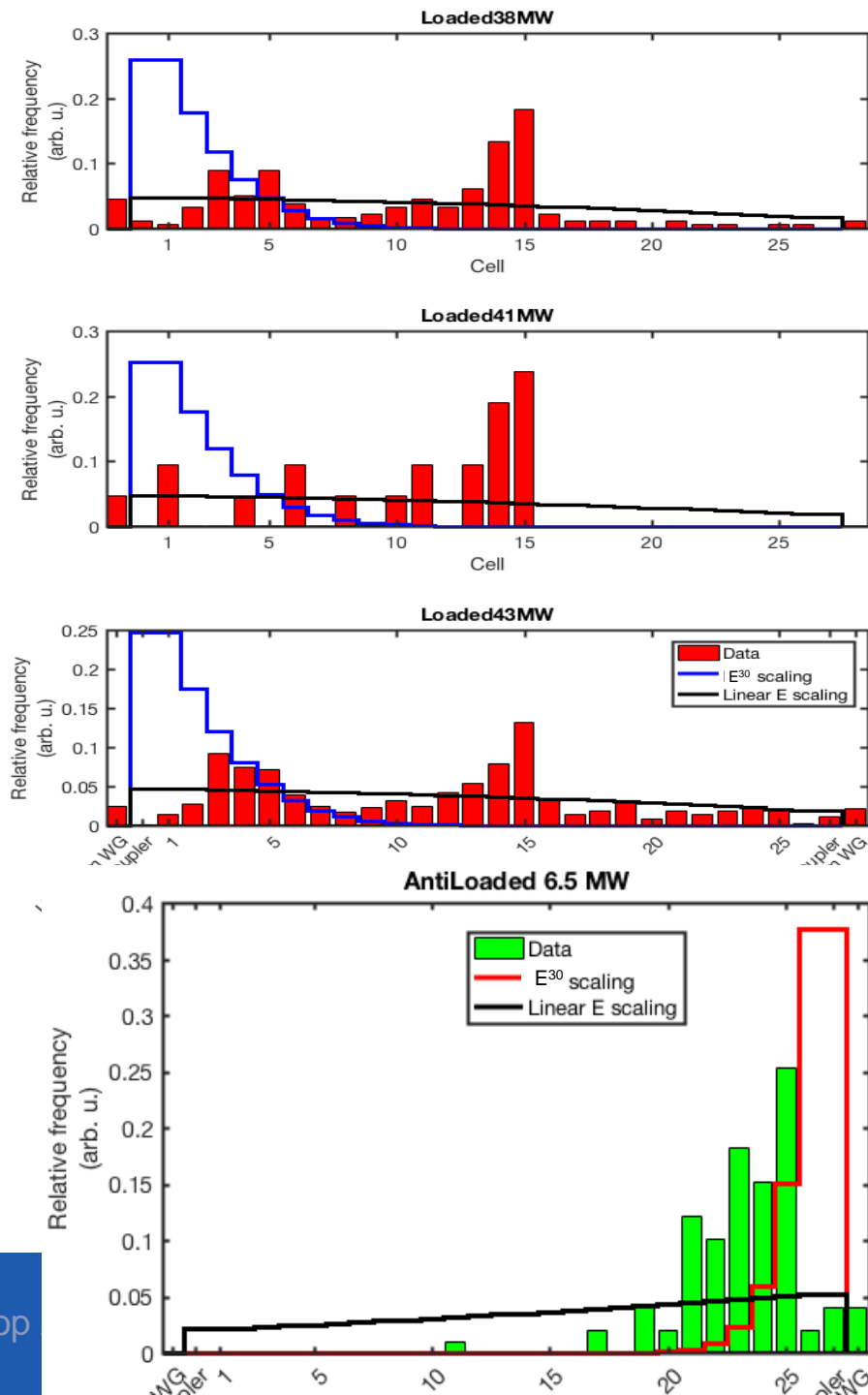
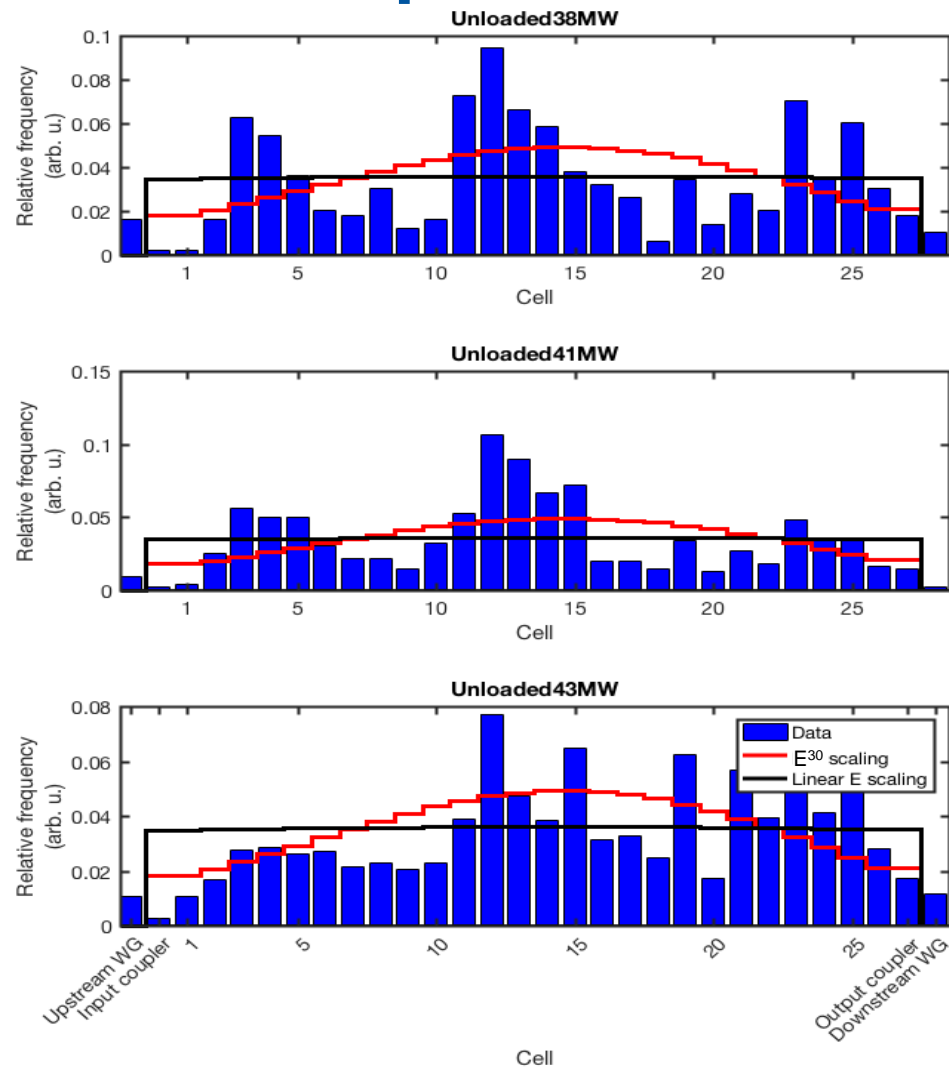
$$BD \text{ probability (\%)} = \frac{\left(\frac{E_{CELL}}{E_{MAX}}\right)^{30}}{\sum \left(\frac{E_{CELL}}{E_{MAX}}\right)^{30}}$$



# BD position



# vs expectation



# Conclusions

- The **BDR** with and without beam **has been measured** for the CLIC-G TD26CC structure
- The **breakdown** rate is generally **lower** when there is the **beam**
- Breakdown **distribution** seems to follow the **gradient profile**, but more data are necessary to understand the scaling law
- Breakdown localization is consistent with **accumulation of the BDs in the front when loaded and at the end when anti-loaded**
- This is a phenomenology study, not the CLIC operation simulation
  - Higher beam current → maximize the effects of the beam
- This suggest the idea of modifying the tapering in order to have a **flatter gradient profile along the loaded structure**

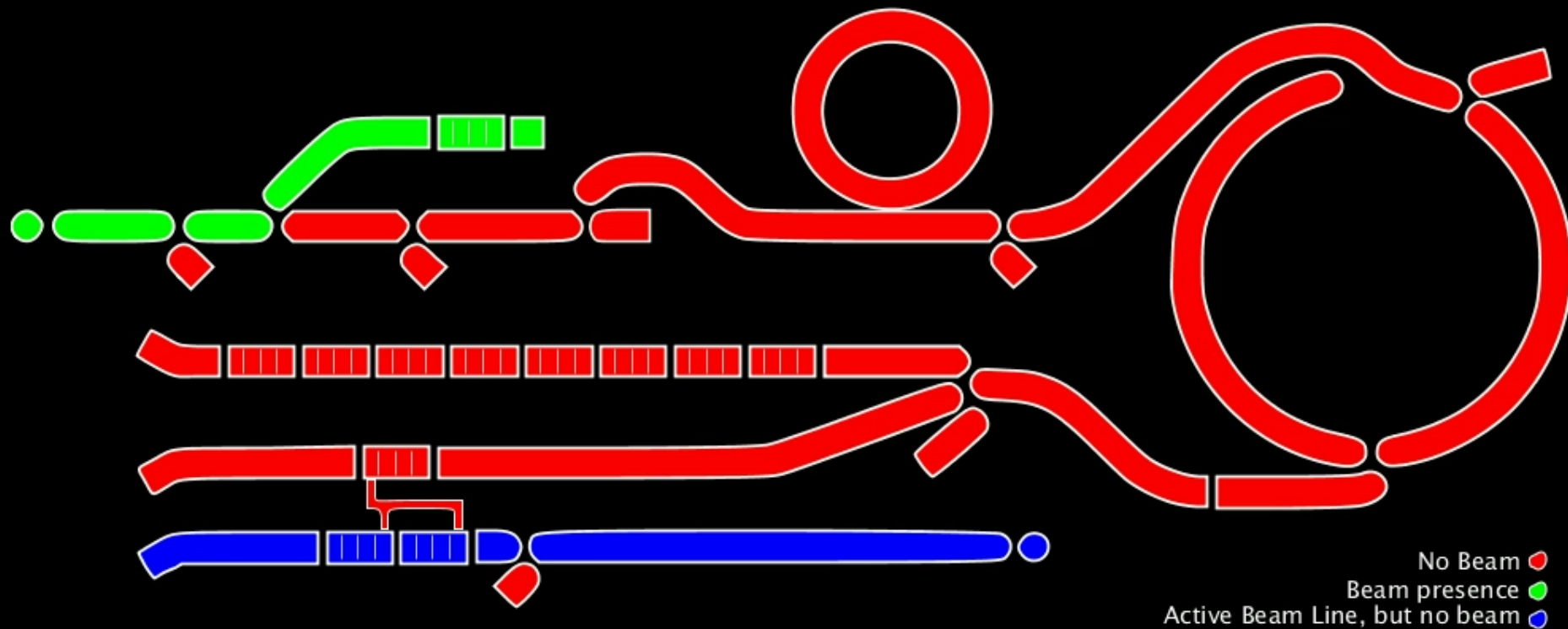
# Future perspective

- In 2016 we **learnt how to do experiments with the beam**
- Comparing loaded and unloaded case at the same average gradient would be interesting. WGs need to be conditioned for running at 100 MV/m loaded
- Some **fluctuations in the BDR** are present. It's not clear why, and needs to be investigated, if this is normal or depends on the input power change
- In any case, our experience highlighted the **necessity of stable running conditions** for long runs. A **long continuous beam time** is necessary

## ACKNOWLEDGMENTS:

**Thanks to the CTF3 & XBOX teams members that contributed to the complex realization of this experiment !!!**

# Experiment: DOGLEG



Comments (7-Mar-2017 11:50)

**Thanks for your  
attention**

Necessary Drive Beam Klystrons Pulsing

true

Necessary Drive Beam Valves Open

true

Califes Klystron Pulsing

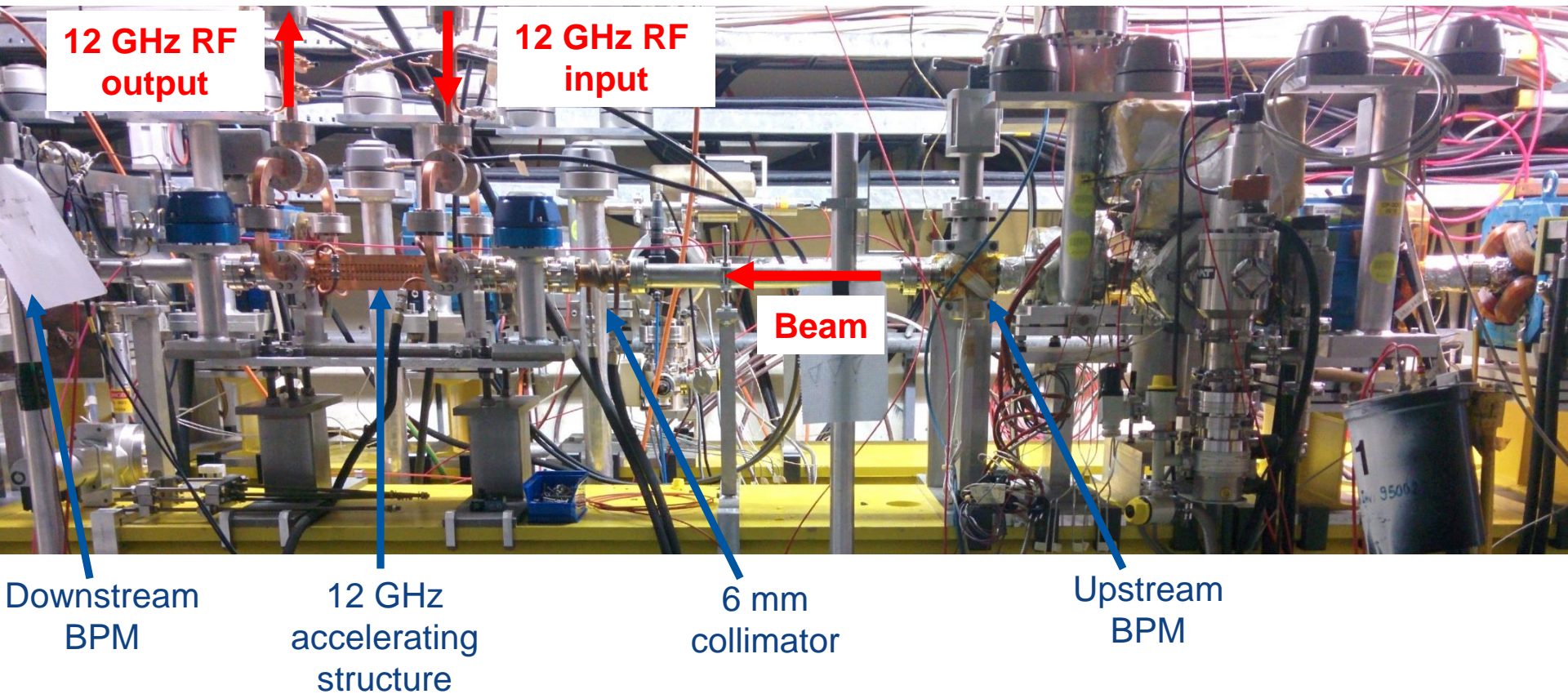
false

Califes Laser Shutter Open

false

# Extra slides

# Diagnostic



# 12 GHz RF source (XBOX1)



## ScandiNova Modulator:

- Designed for 400kV, 300A, 3.25us HV pulse width FWHM, 1.5us RF pulse width at 50Hz repetition rate



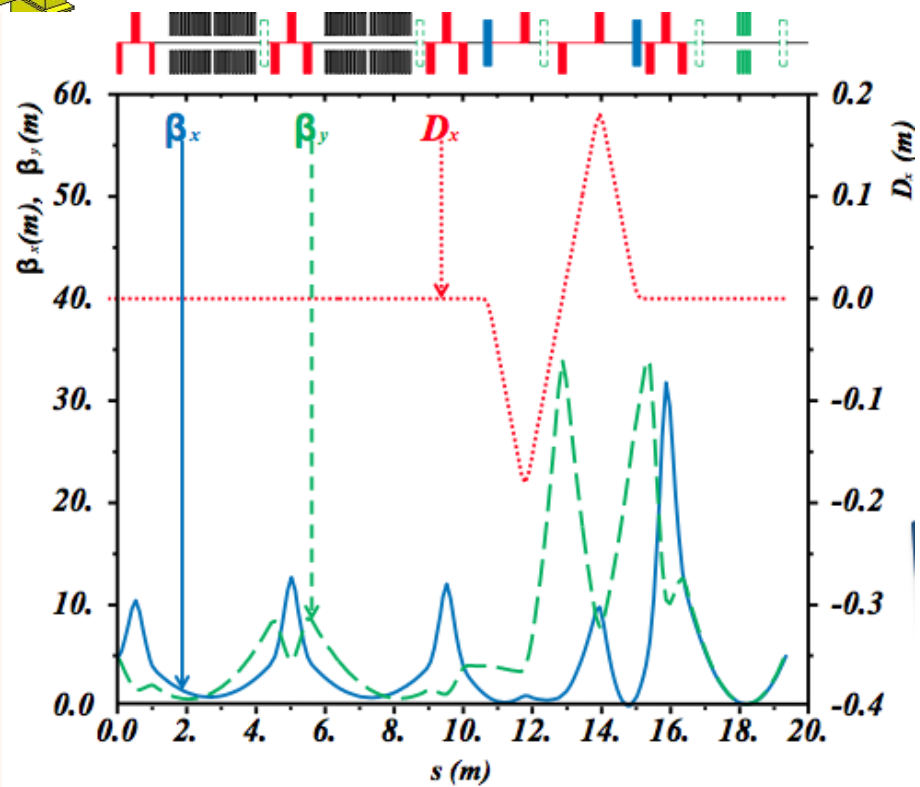
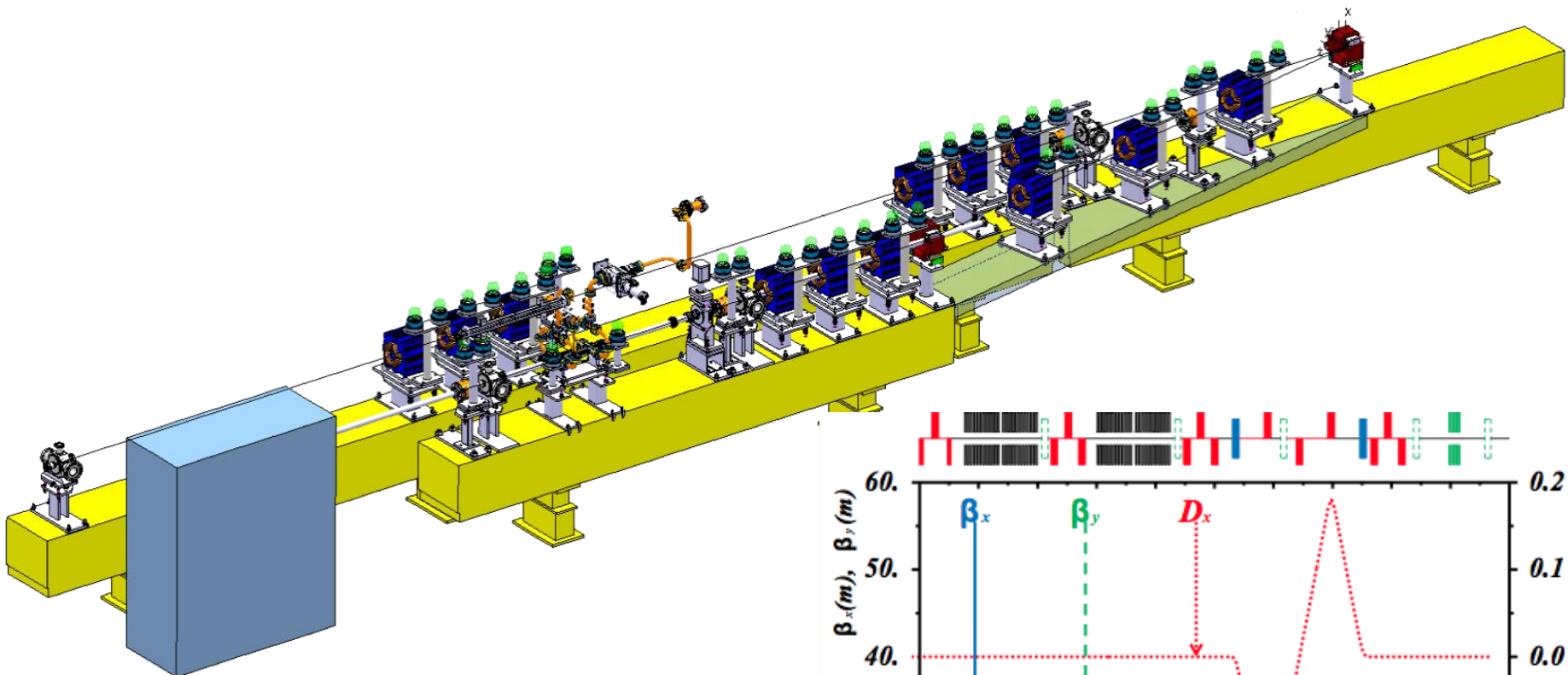
## XL5 klystron:

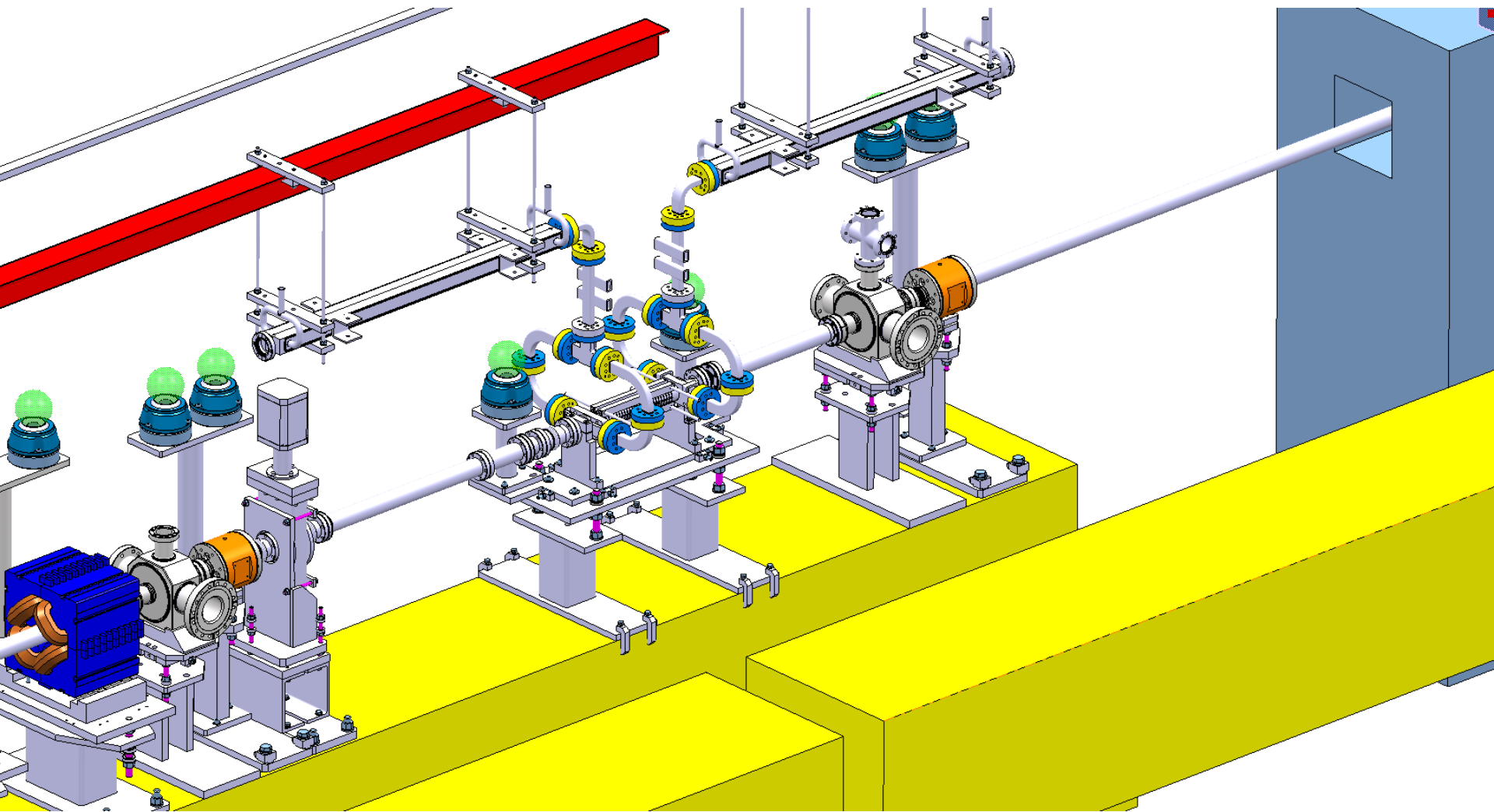
- 50MW, 1.5us RF pulses
- 50Hz repetition rate at 400kV, 300A, 600W RF drive power
- Working frequency 11.99424GHz



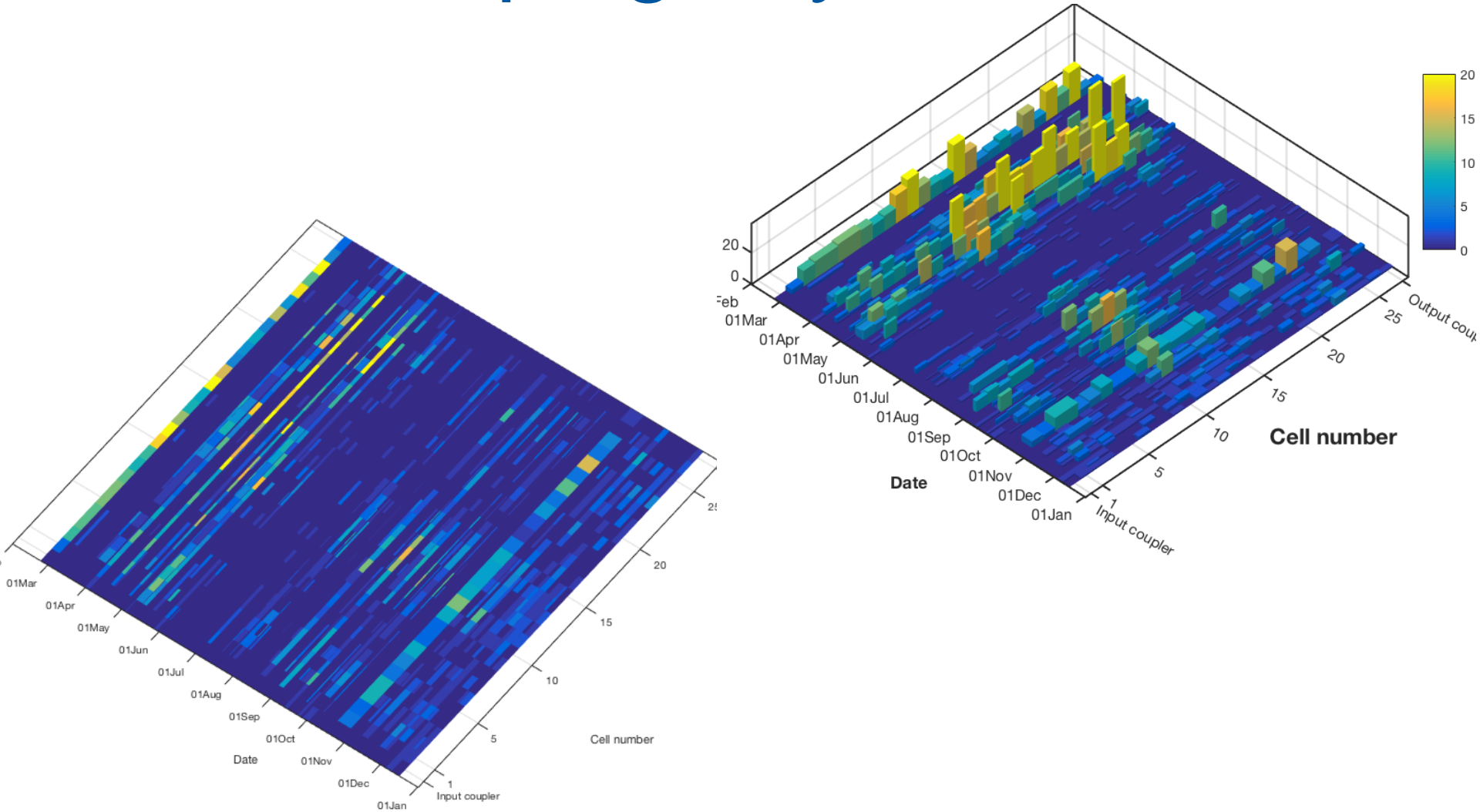
## SLED-I type pulse compressor:

- Power gain  $\sim 3$
- $Q_{\text{loaded}} = 2.375 \times 10^4$
- Beta = 4.27
- $Q_0 = 1.31 \times 10^5$
- 5% power loss





# 2016 campaign by run



### Measured BDR

