High Power Testing of Distributed Coupling Structures at SLAC and KEK

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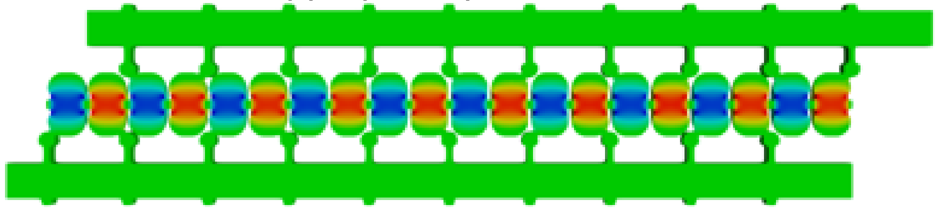
Agenda

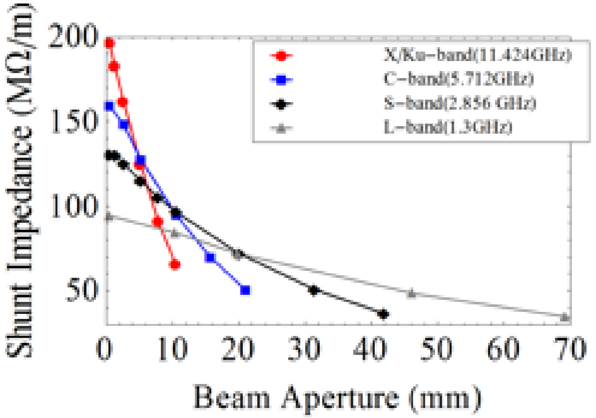
1. Distributed Coupling Structure (DCS) Concept
2. Prototype Structures
3. Tuning Procedure
4. Test facilities – XTA @ SLAC and Nextef @ KEK
5. High power testing of DCS #2 at KEK
6. Breakdown Rates
7. Early results from DCS #1 Cryo (Liquid N_2) test
8. Future Work

Distributed Coupling Accelerator Structures:
A new Paradigm in High Gradient Linacs

Carefully designed to provide equal power distribution and appropriate phase to each cell

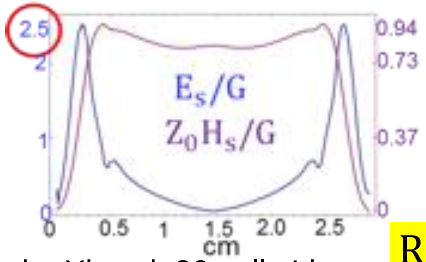

$\lambda_g/2 \sim \lambda$

Cavities can be optimized without the constraint usually applied from the coupling between adjacent cavities.



New Scaling Laws Determine the Best Performance for Accelerating Structures

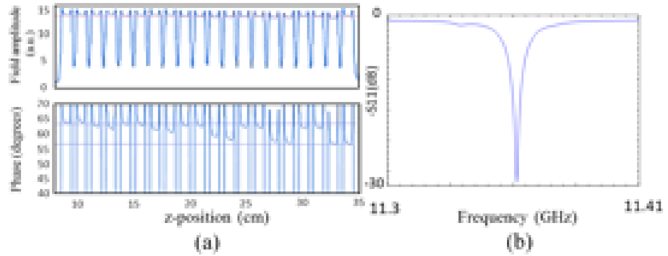
Designed to minimize surface magnetic field

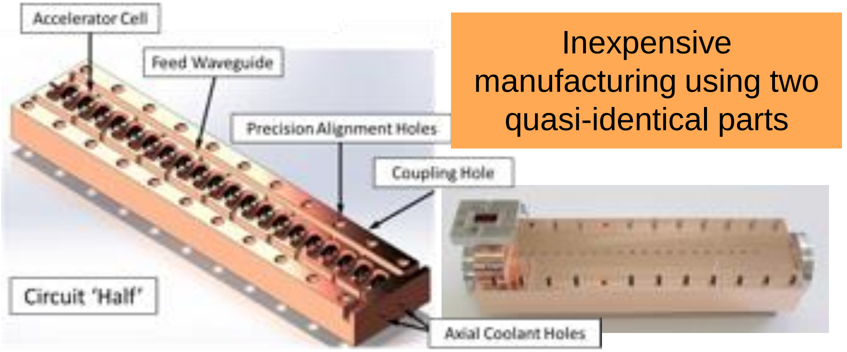


π-mode, Xband, 20 cells Linac

$R_{shunt} = 155\ M\Omega/m$

Easy tuning and single frequency rather than 20



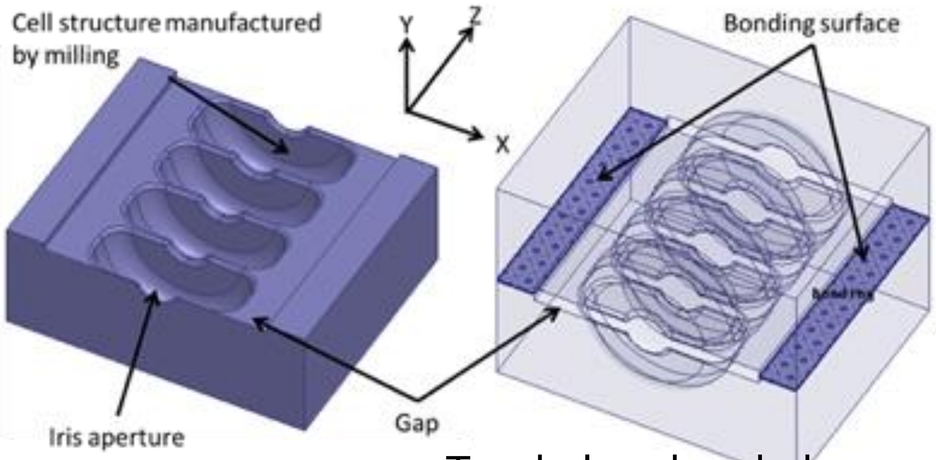


Inexpensive manufacturing using two quasi-identical parts

Compact structures with increased shunt impedance – useful for large user facilities & compact high-efficiency linac systems

Novel Fabrication Methods for Accelerating Structures are Compatible with Hard Metals and Cost Effective

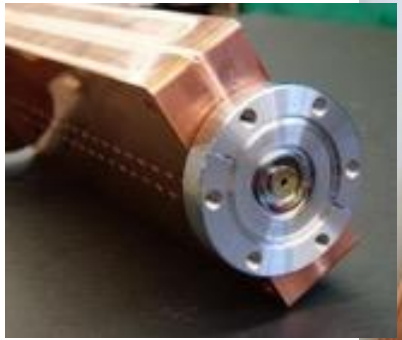
- Structure is fabricated in two symmetric halves, and joined afterward
- Novel geometry: open structure – no RF currents through the joint
- Compatible with various materials: standard OFE copper, hardened copper, Cu alloys
- Machining methods: conventional milling, EDM
- Various joining methods: brazing, bonding, e-beam welding, TIG welding, clamping



Solid Model

Two halves bonded together

V. A. Dolgashev, A. Grudiev



Demonstrated with Standing and Traveling Wave Structure

S. Tantawi, P. Borchard, Z. Li

Developing new manufacturing techniques to implement advanced materials in practical accelerating structures and reduce costs

DCS Prototypes

SLAC is aggressively studying the limits of the DCS topology:
Cell optimization, materials, fabrication methods, and temperature

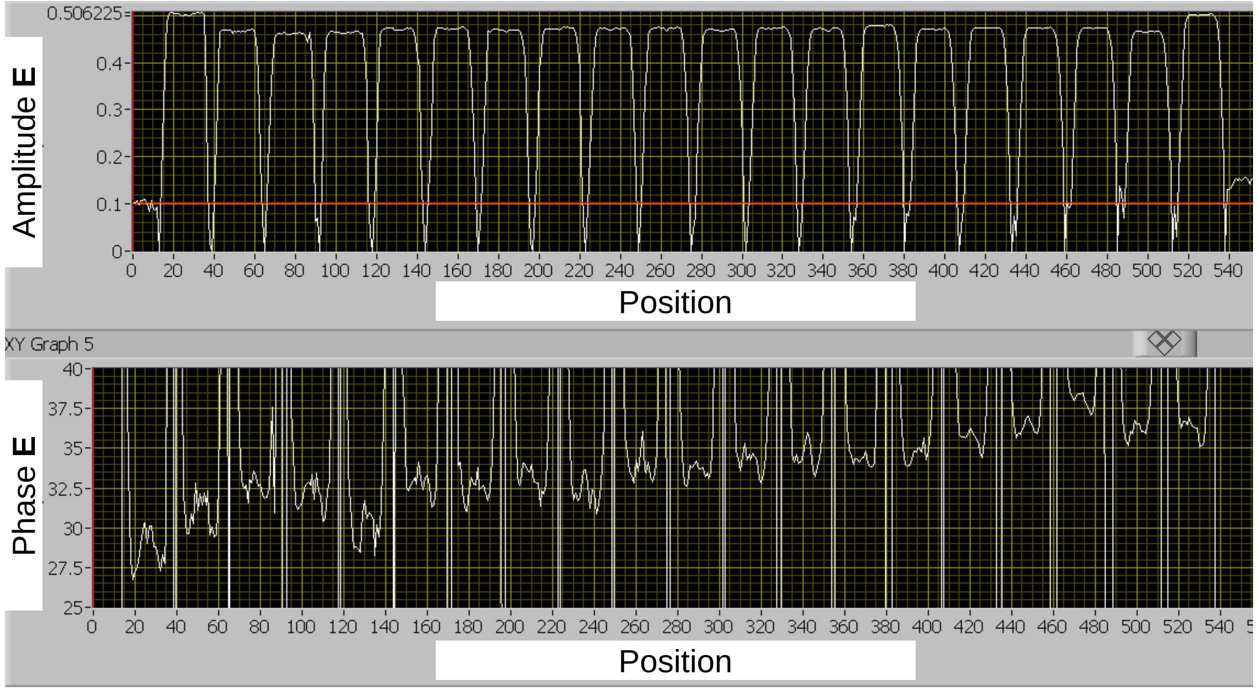
	#1 – Baseline	#2 – Soft Cu EDM	#1a – LN-cooled Baseline	#3 – Hard Cu EBW	#4 – CuAg Clamped
Test Status	Completed	Completed	In Progress	Future	Future
Test Facility	XTA / SLAC	Nextef / KEK	XTA / SLAC	XTA / SLAC	-
Max. Gradient @ 100 ns (MV/m)	140	110	150 & increasing	-	-
Shunt Impedance (MΩ/m)	156	156	~375	156	161 (Optimized Curvature)
Peak Surface **E** / Acc. Gradient	2.5	2.5	2.5	2.5	2.0 (Optimized Curvature)
Material	Soft OFE Cu	Soft OFE Cu	Soft Cu at 77 K	Hard Cu	CuAg Alloy
Fabrication	Milling	EDM	Milling	Milling	Milling
Joining Method	CuAu Braze	CuAu Braze	CuAu Braze	E-beam Weld	Cold clamping
Tuning Method	Push/pull	Push/pull	Push/pull	Push only	Push only
Frequency (GHz)	11.400	11.421	11.439	-	-

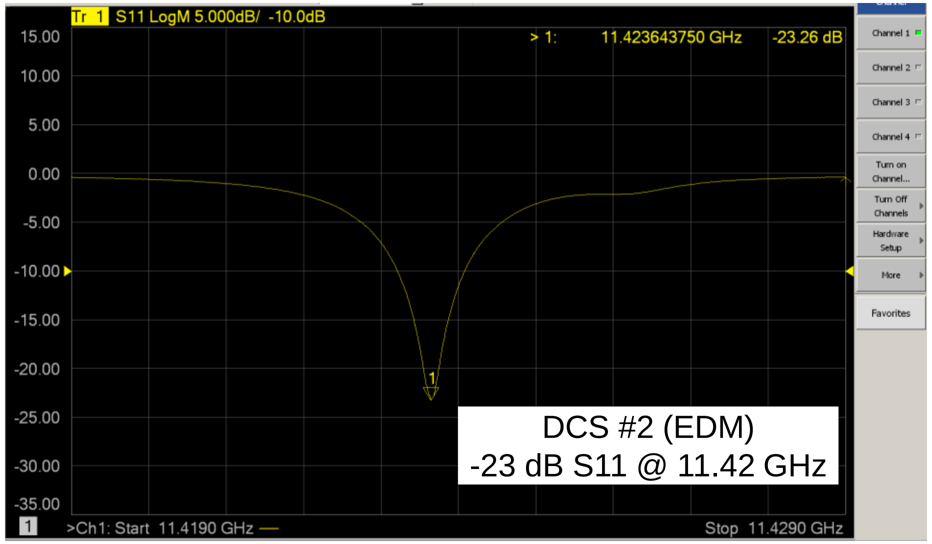
Tuning

Structures are tuned using translatable shorting rods

- Negligible coupling through iris between adjacent cells
- Short out all cells but one, and tune independently
  - Push/pull tuners installed on soft Cu structures
  - Harder materials only allow for push tuning
- Verified with bead pull measurements & pulsed RF cold test

Shorting Rods

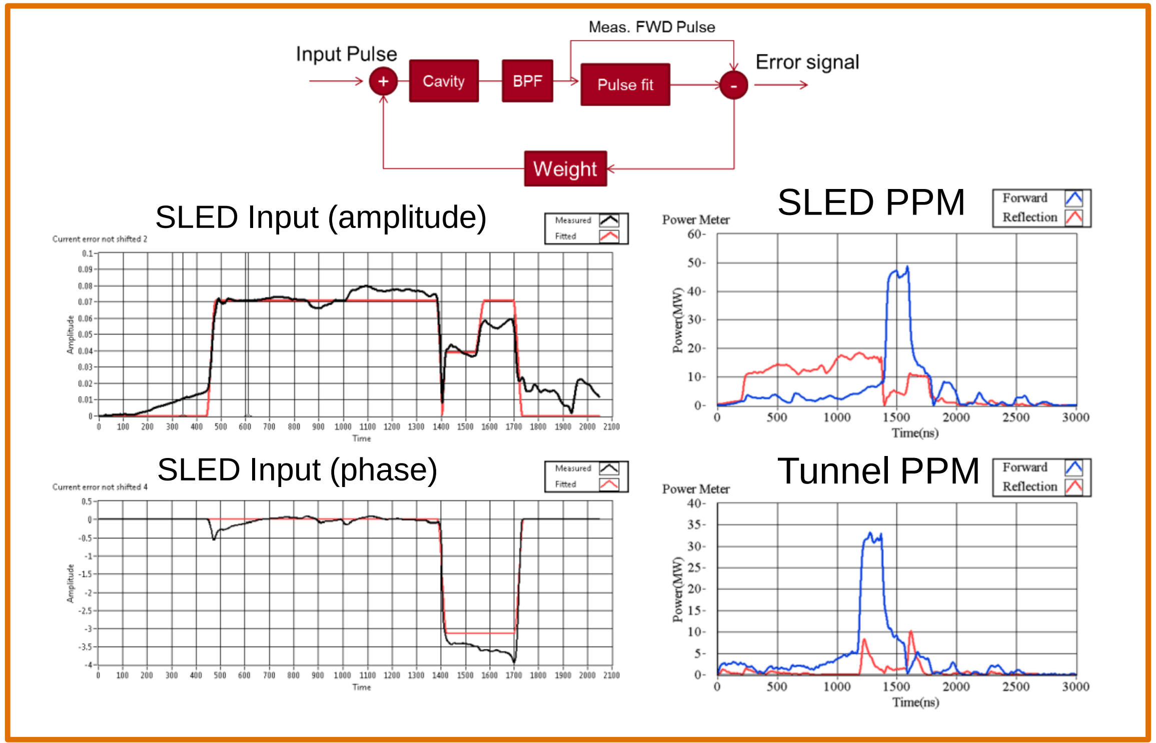


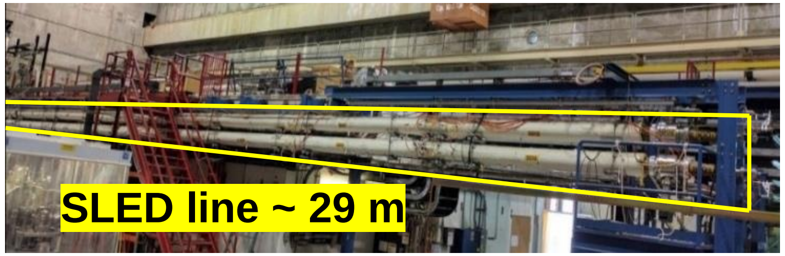


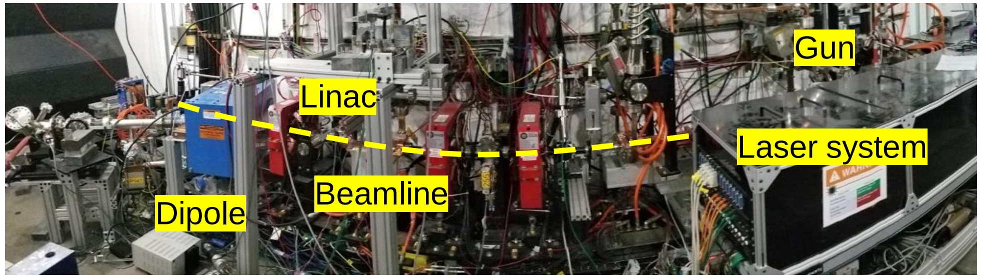
Test Facility – X-band Test Accelerator (XTA) @ SLAC

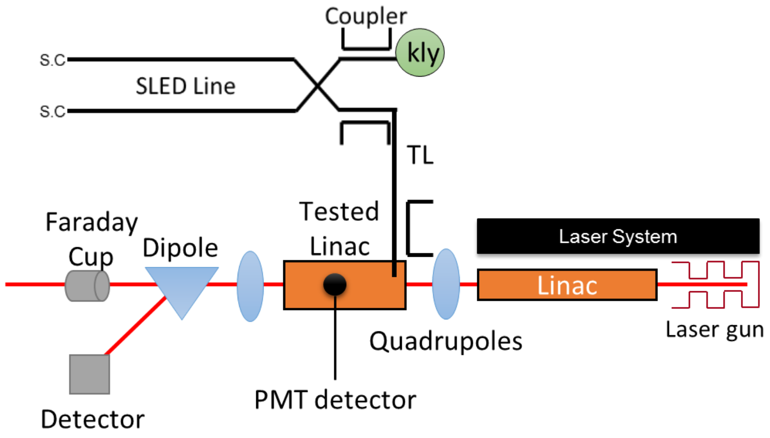
DCS #1 – Baseline, soft copper – tested at XTA

- SLED-II pulse compressor → >100 MW available
- Pulse corrections implemented for constant amplitude & phase at target gradient
- Breakdowns detected by dark current monitors & confirmed by RF waveforms
- Liquid N_2 vessel later installed for high power cryo test







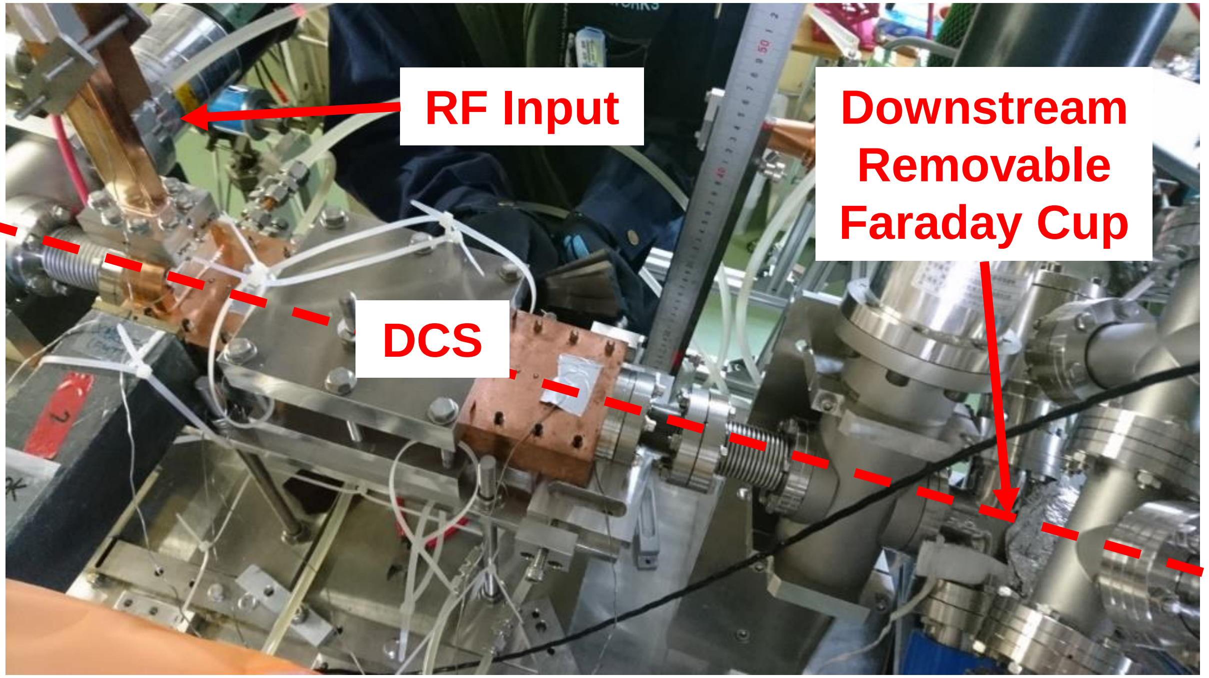


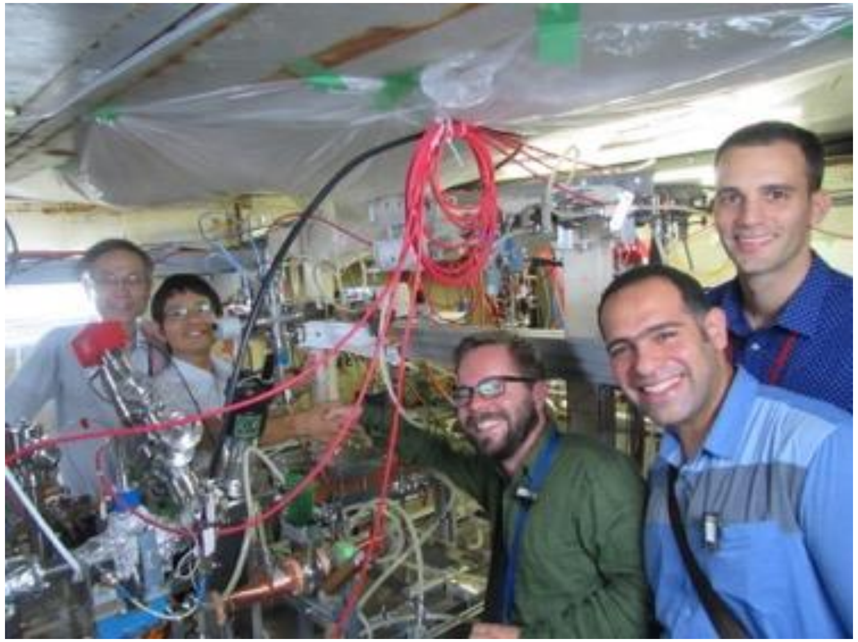
M. Nasr, S. Tantawi

Test Facility – Nextef Shield-A @ KEK

DCS #2 – Soft copper EDM – tested at KEK

- 2x 40 MW, power combined klystrons – no pulse compressor
- Pulse corrections to minimize RF reflection during the pulse
- Two identical Faraday cups upstream & downstream
- RF power & scope values recorded for every pulse
- All waveforms are recorded for set of 10x pulses before BD



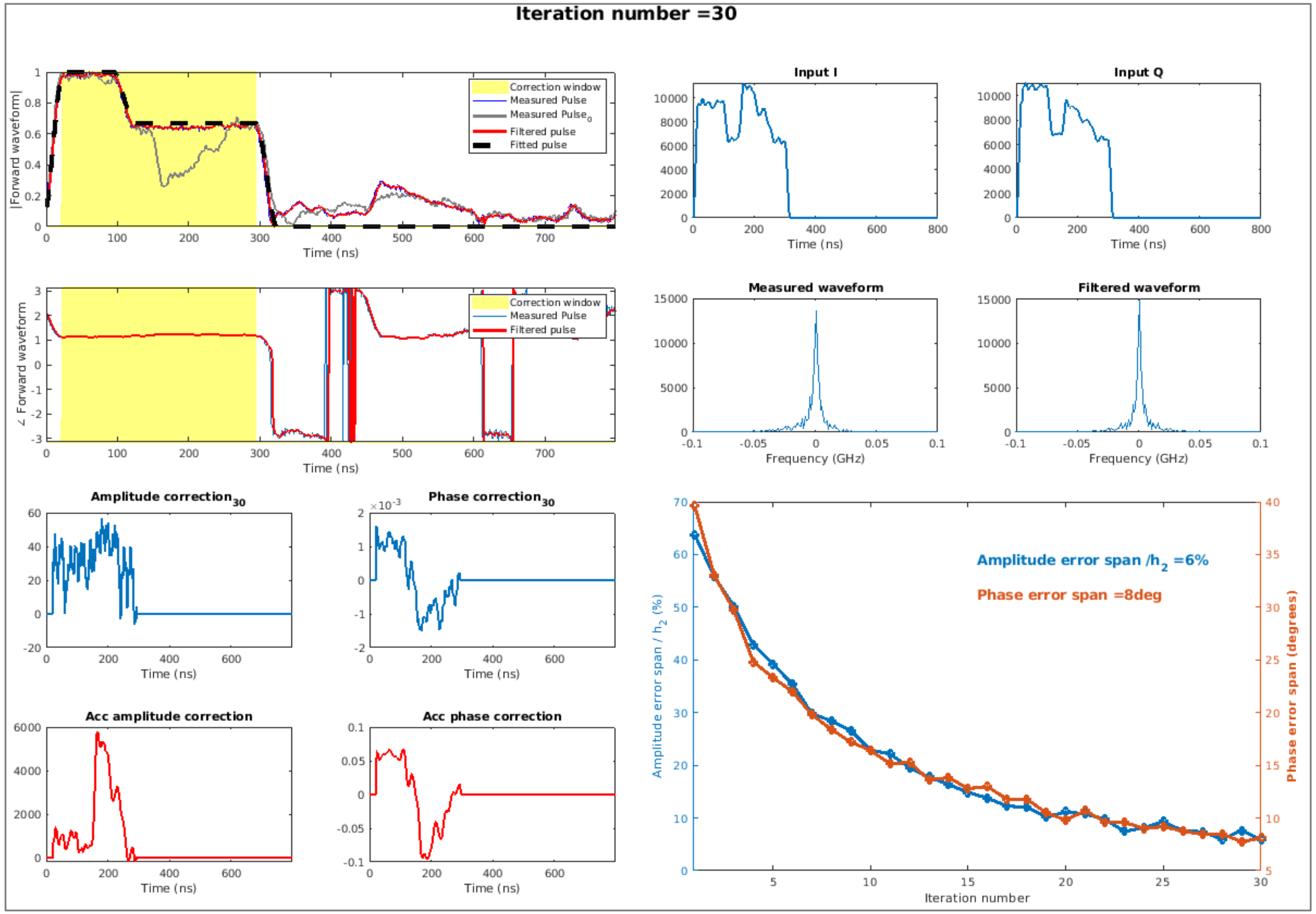


US – Japan Collaboration

Pulse Shape Correction – Implemented at KEK

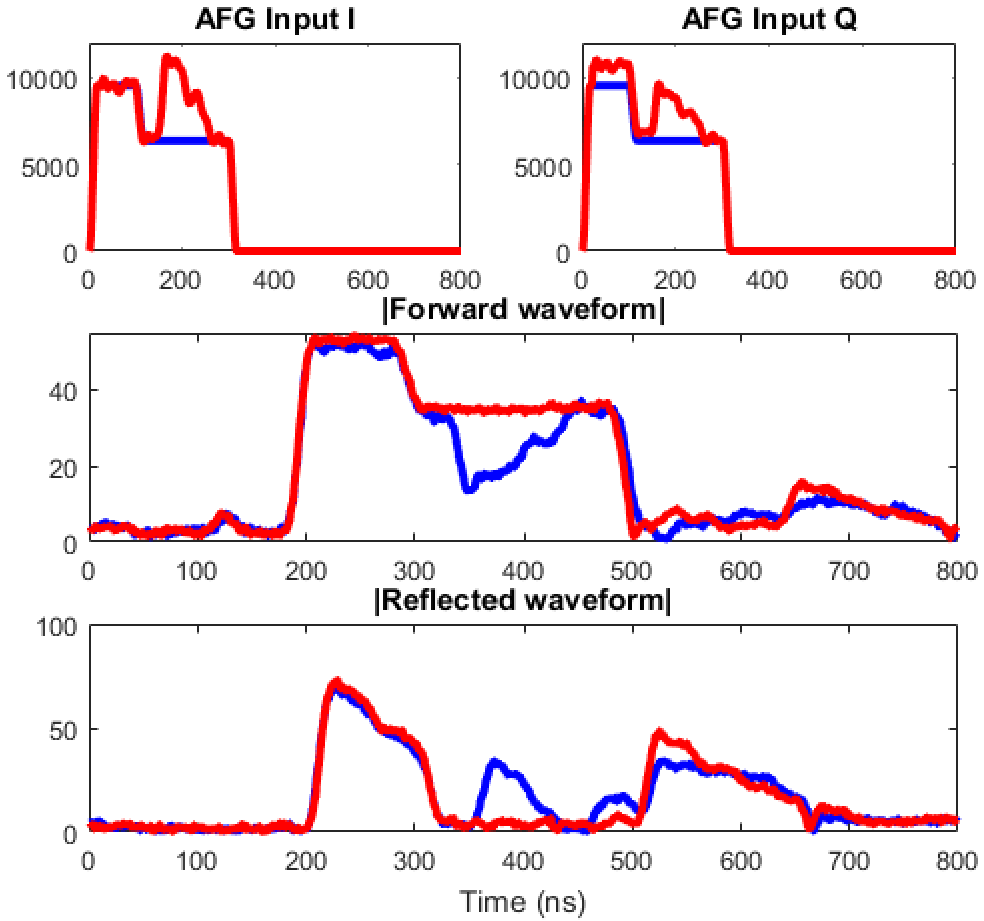
Pulse shaping @ KEK implemented using I/Q modulation

Assume ideal I/Q → measure RF amp/phase → Adjust I/Q → Iterate



Blue: Initial I/Q, Forward/Reflected RF

Red: Final I/Q, Corrected RF Waveforms



Forward & Reflected RF Waveforms

SLAC

100ns charging pulse
+ 100ns flat pulse

Yellow: Forward
Blue: Reflected

Forward pulse

Initial full reflection from empty structure

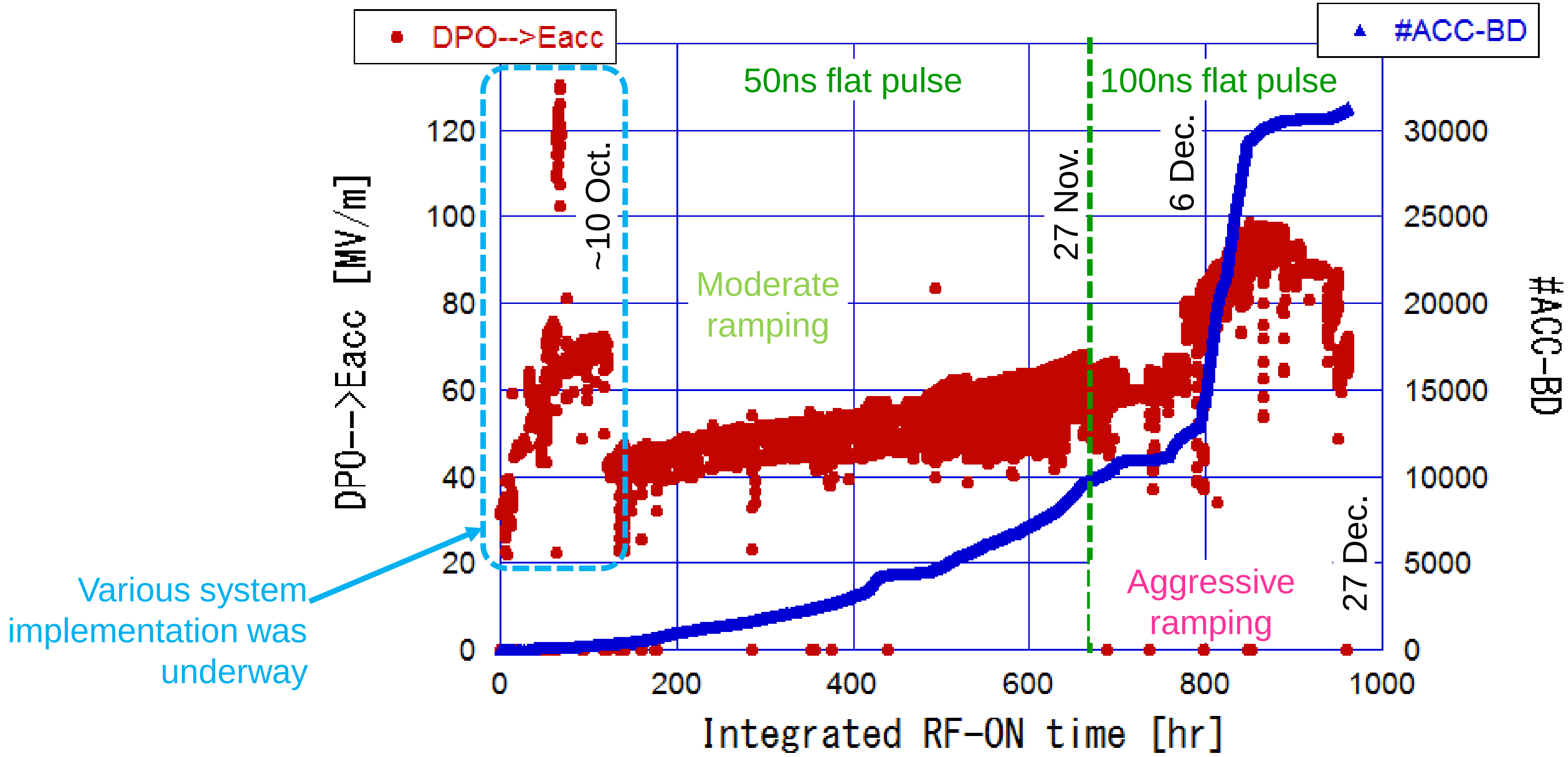
Constant gradient

RF Discharge from structure

Return of reflected pulse delayed by 112ns

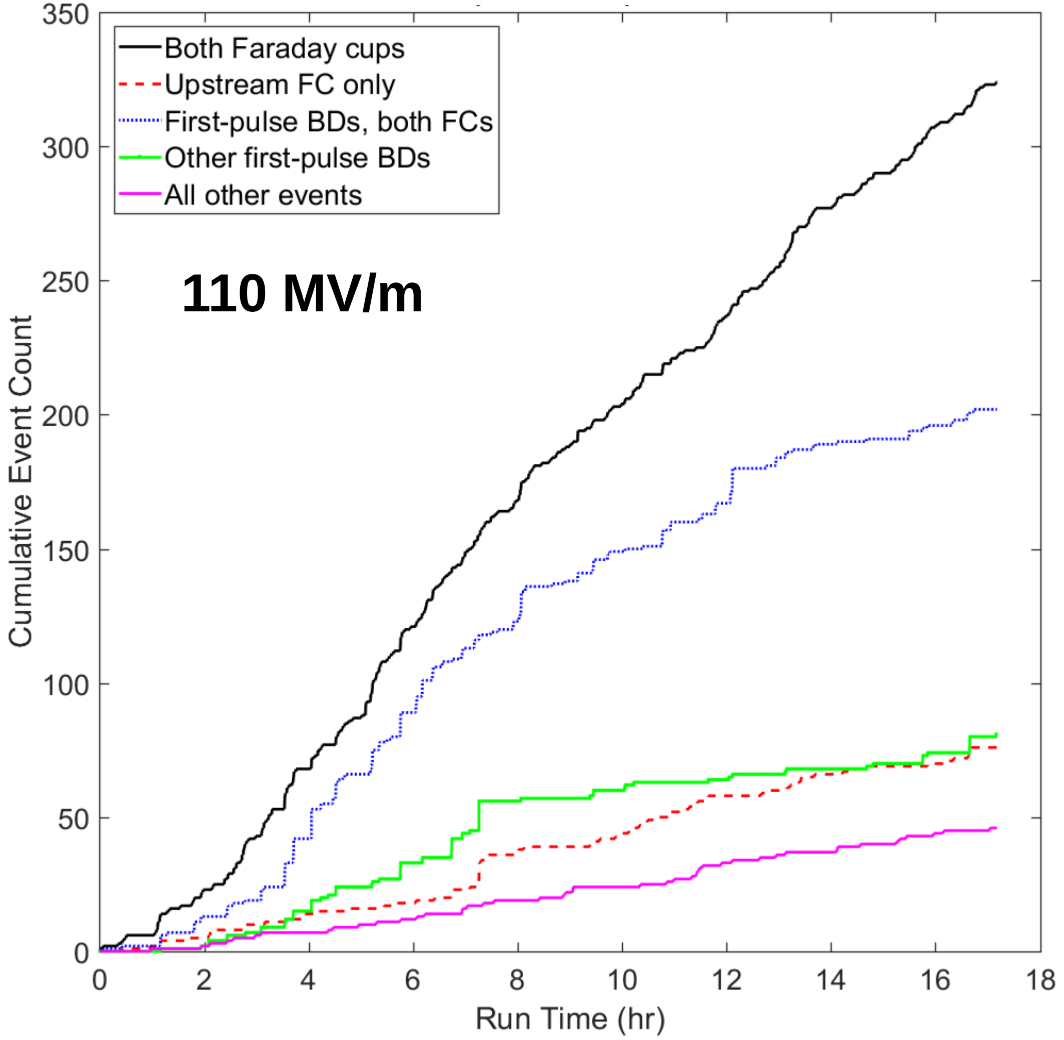
DCS #2 - Processing History

- Initial processing procedure: hold maximum BDR; moderate ramping of power
- Later, “aggressive processing: applied a fixed “target” power and allowed any BDR
  - Experience with DCS #1 showed that excessive BDR did not degrade structure performance
- At each target gradient, BDR vs. time converged after a few days

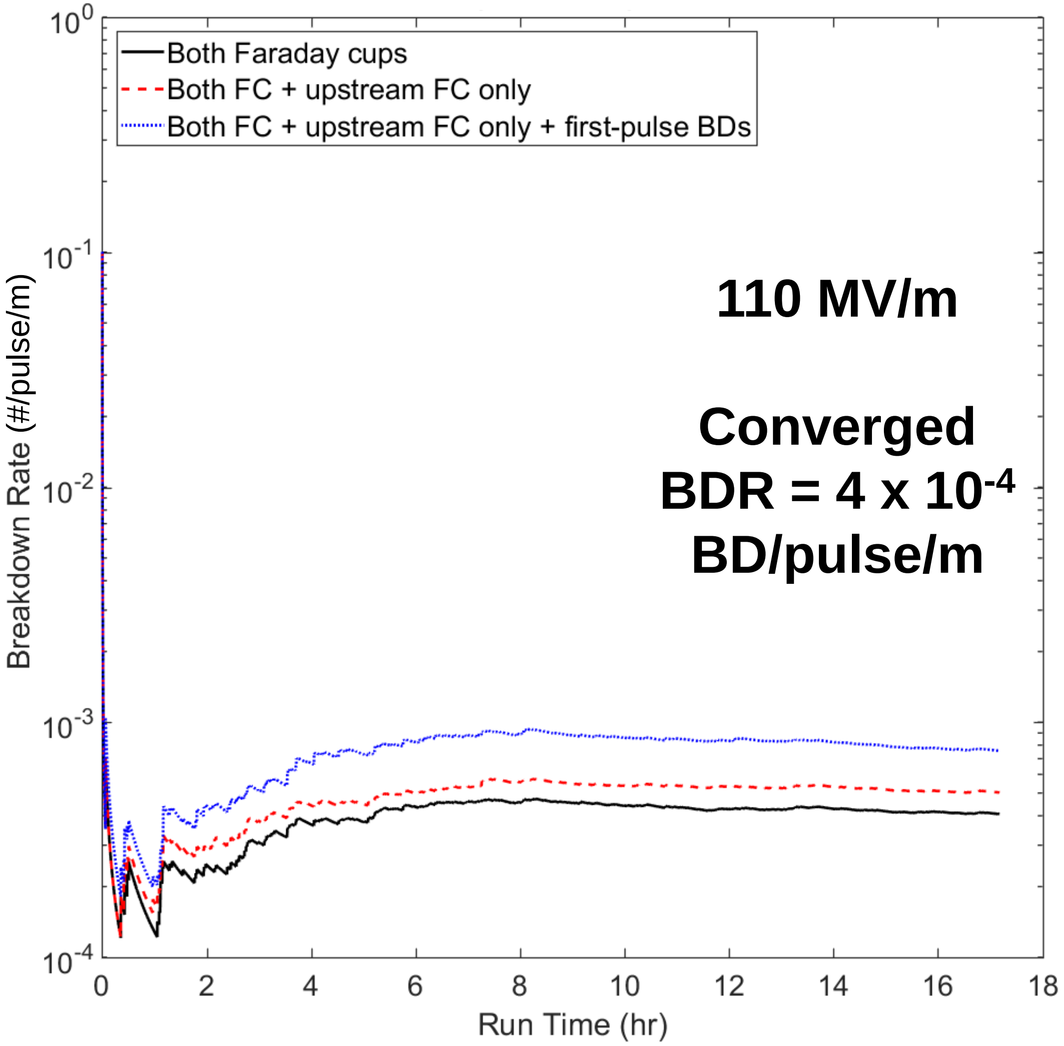


DCS #2 - BDR evaluation at 110 MV/m

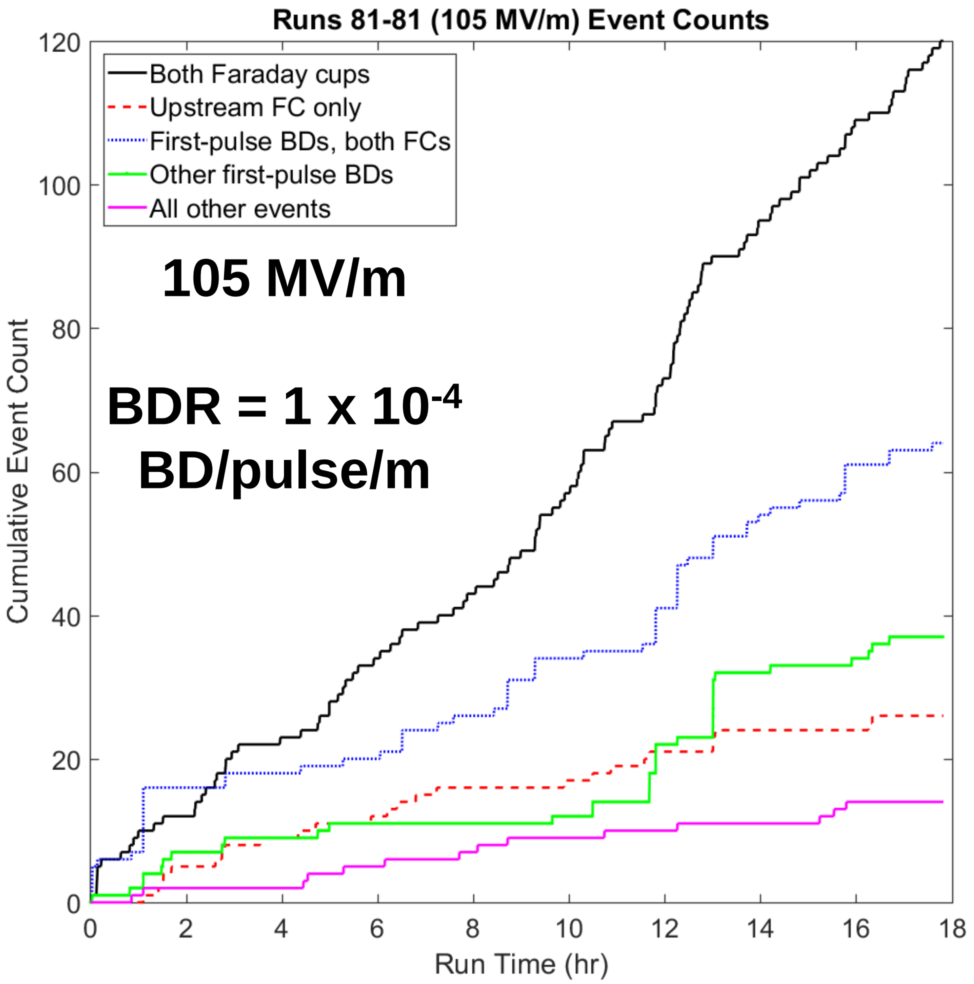
Event counts by type

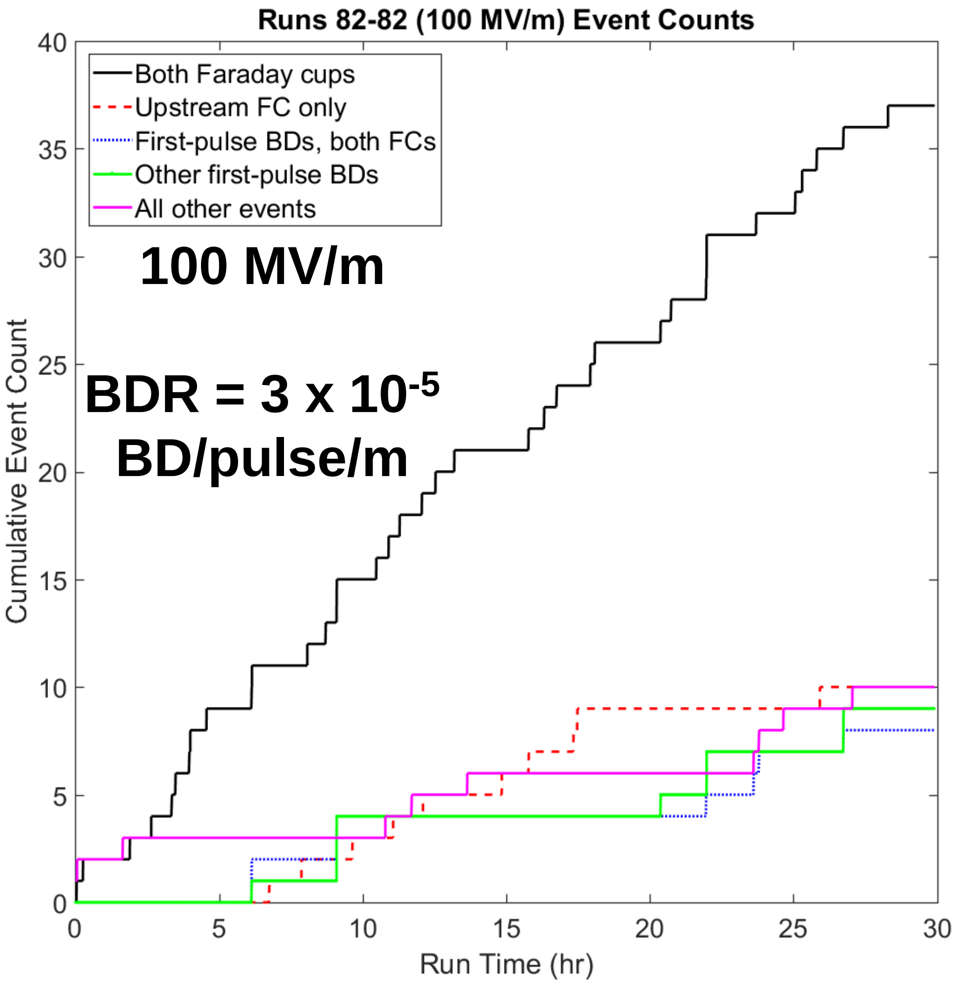


Breakdown rate by type

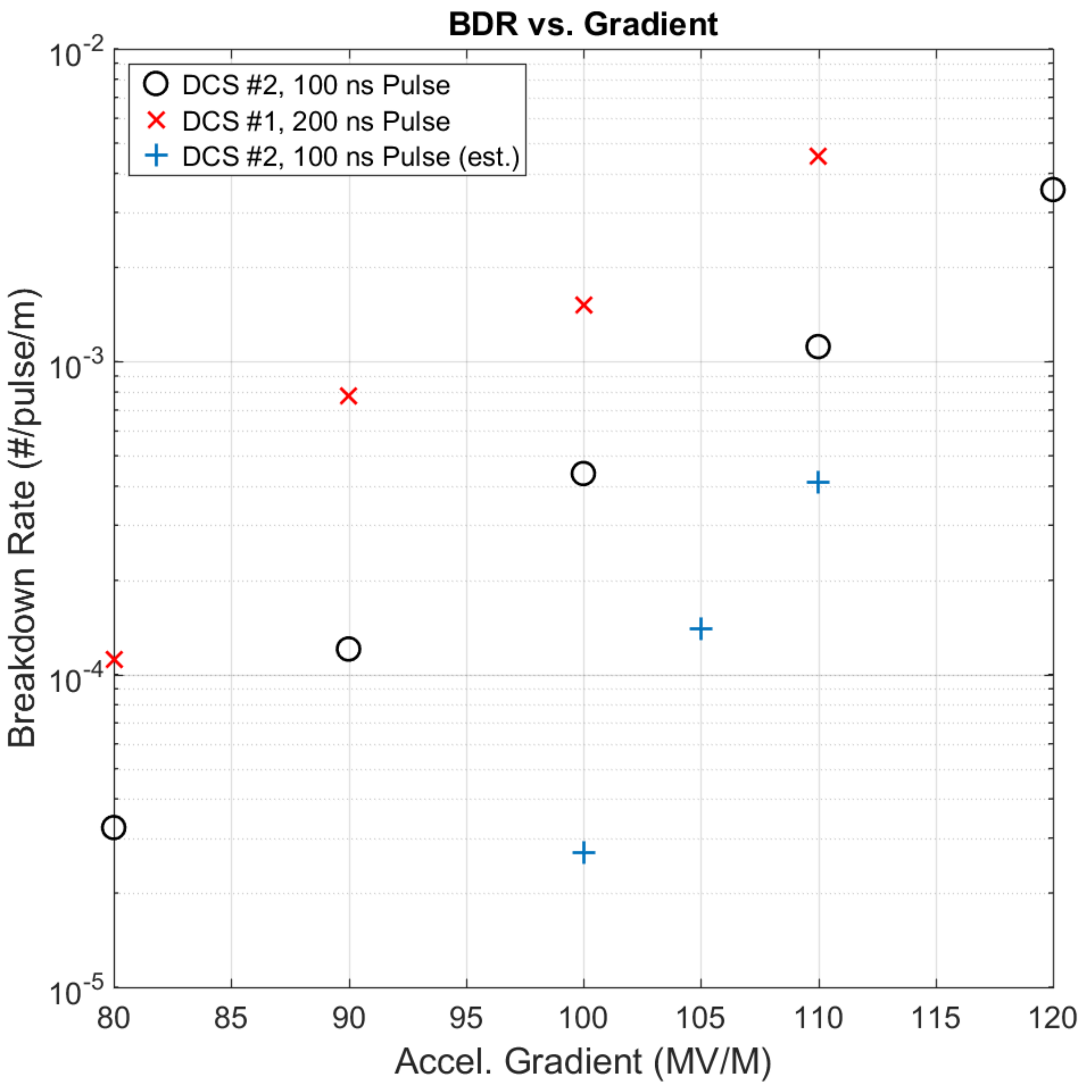


DCS #2 - BDR evaluation run 81 & 82



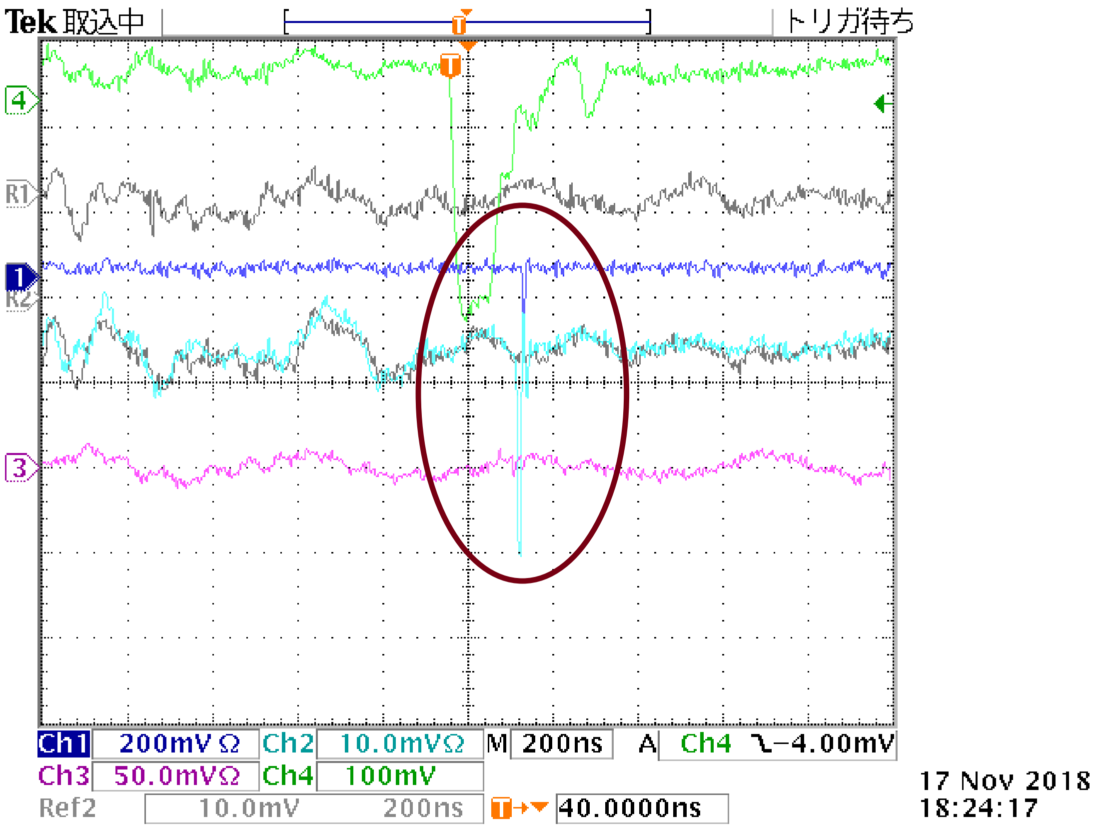


Breakdown Rates vs. Accelerating Gradient



- **Initial BDR estimate for DCS #2 is lower than DCS #1**
  - Long-duration uninterrupted processing time at KEK was extremely beneficial
  - Aggressive processing at 110 MV/m, then statistics taken at 105, 100 MV/m
- **For DCS #1, slope of BDR vs E_{acc} is the same with different pulse widths**
- **More detailed analysis of DCS #2 breakdown statistics is in process**
  - **Filter out “off-target” pulses**
  - **Screening for false positives**
  - **Analysis of RF pulse distortion**

Breakdown Properties



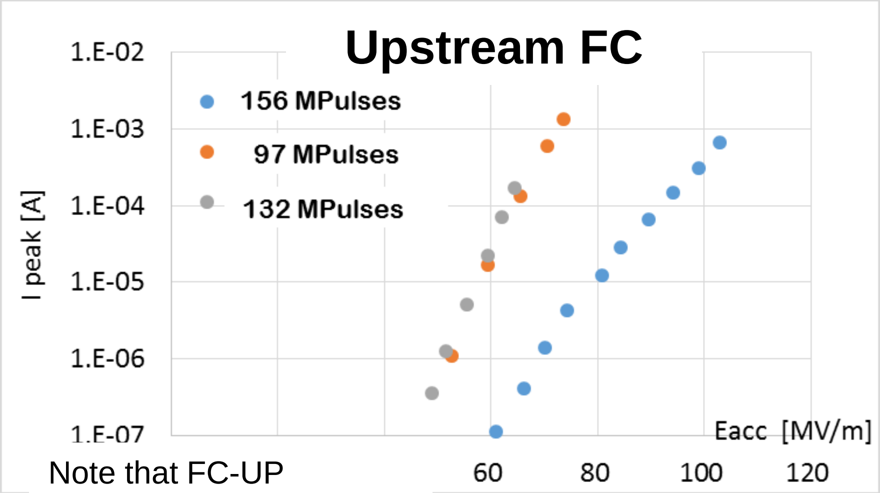
It appears that many events could be called "soft breakdowns"

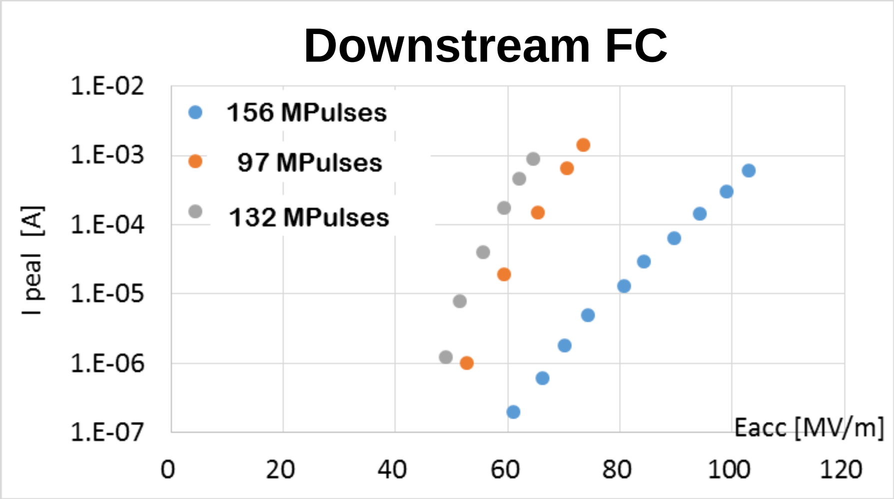
- Extremely brief (few ns) spike in FC signals
- Little integrated energy in event
- No vacuum activity detected
- Nothing picked up on acoustic sensors
- Distortion of RF waveforms is very subtle

Higher fraction of soft breakdowns may be unique to distributed coupling design

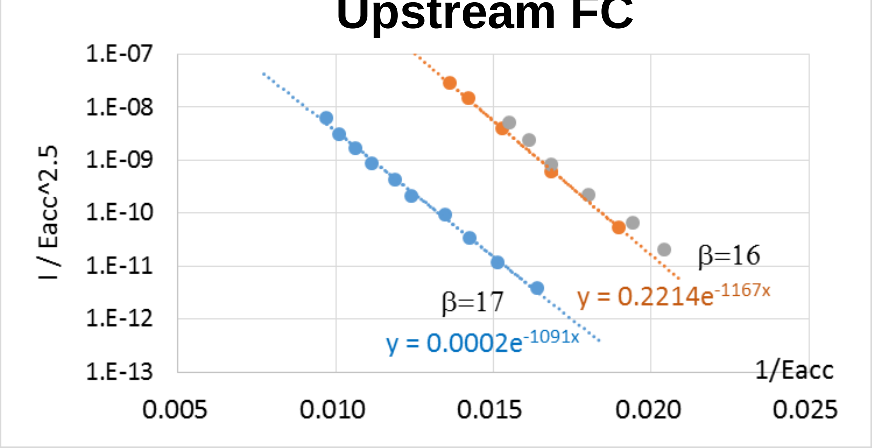
- Less power deposited in a single cell
- Further study is needed of soft breakdown impact on other cells & total gradient

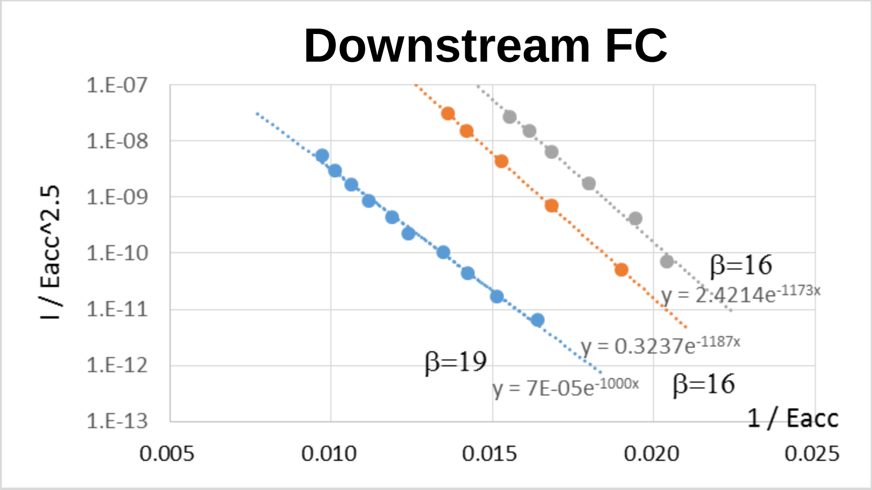
DCS #2 – Peak dark current and Fowler-Nordheim





Note that FC-UP acceptance was increased between 97 to 132 Mpulses.





Dark current decreasing with processing

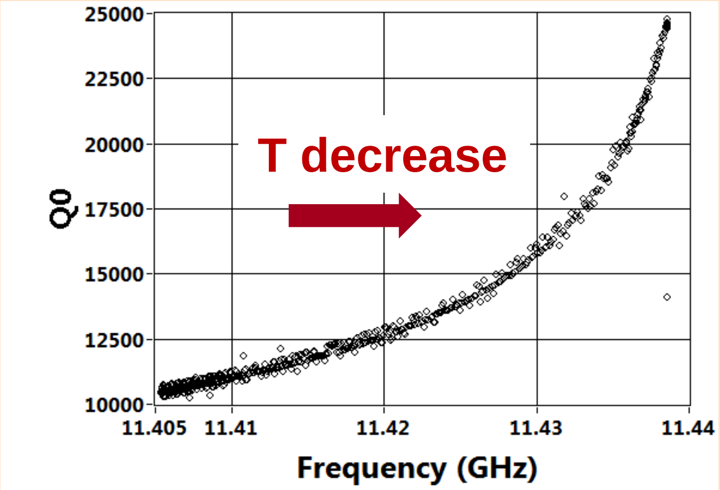
10 μA dark current at 80 MV/m

Field enhancement factor β ranges from 16-19

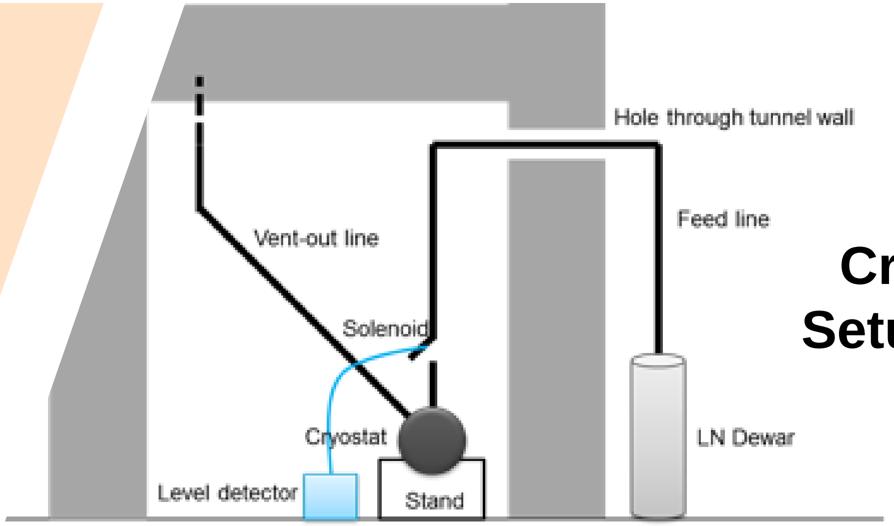
- Low, but consistent between different runs and Faraday cups

Cryogenic-Copper Accelerating Structures: New Frontier for Beam Brightness, Efficiency and Cost-Capability

- Increased conductivity and hardness enables higher gradients
- Dramatic reduction in cost of system including cryogenics at 77K
- 2.5X less power establishing gradient allows for heavy beam loading – higher system efficiency



Increase in Q_0 by a factor of 2.5



Cryo-DCS Setup at XTA

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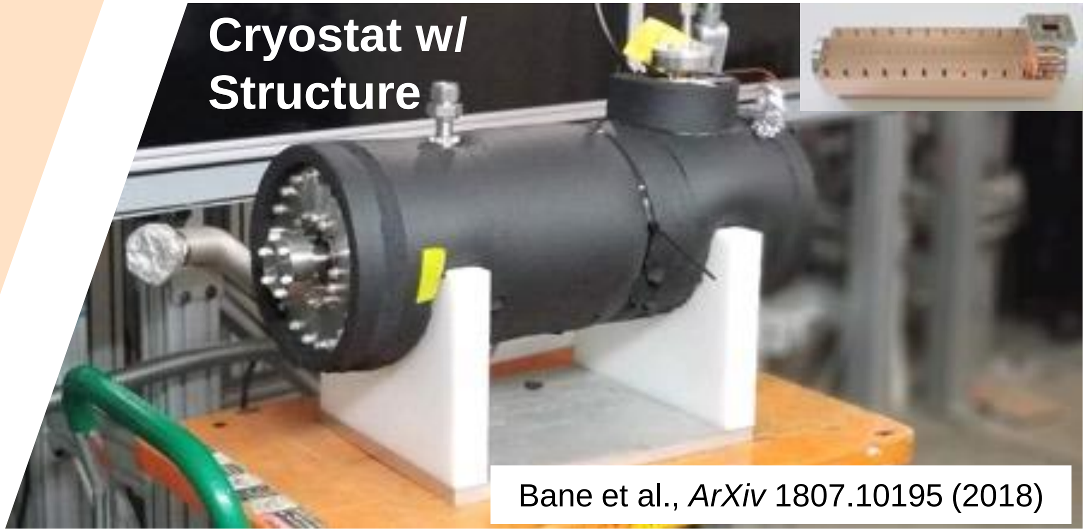


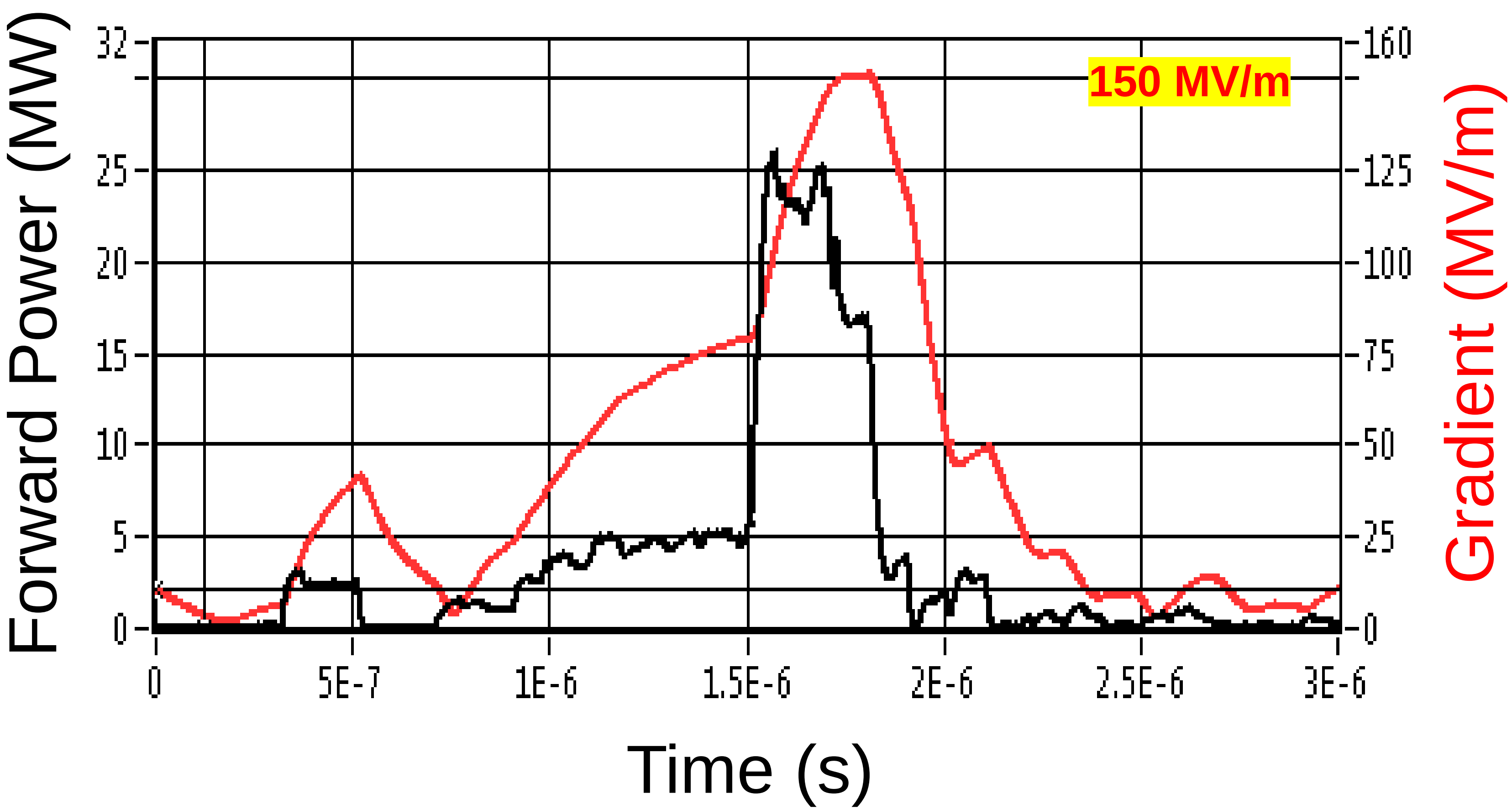
Bane et al., *ArXiv* 1807.10195 (2018)

DCS #1 Cryo Test – Currently at 150 MV/m

DCS #1 is currently stable at 150 MV/m in LN test

No practical limit has been reached yet – continuing to push higher

Long-duration LN X-band test will be needed to fully characterize BDR



M. Nasr et. al.

Future Work

Cryo-cooled DCS test is ongoing at NLCTA

- Continuing to push gradients above 150 MV/m

Analysis of EDM DCS test at KEK

- More detailed analysis of breakdown rates
- Analysis of Faraday cup signals (timing & amplitude) to estimate breakdown locations
- Modeling of structure dark current using ACE3P
- Structure autopsy

Future DCS testing

- Installation of hard Cu EBW structure at NLCTA for high power test
- Tuning and high power test of clamped CuAg structure
- Investigations of breakdown severity in DCS – effects on other cells and total gradient
- High power testing at XTA with full beam