CLIC Crab Project Summary

G. Burt, A. Dexter, D. Constable, S. Smith, B. Woolley*, V. Hill, S. Kariman*

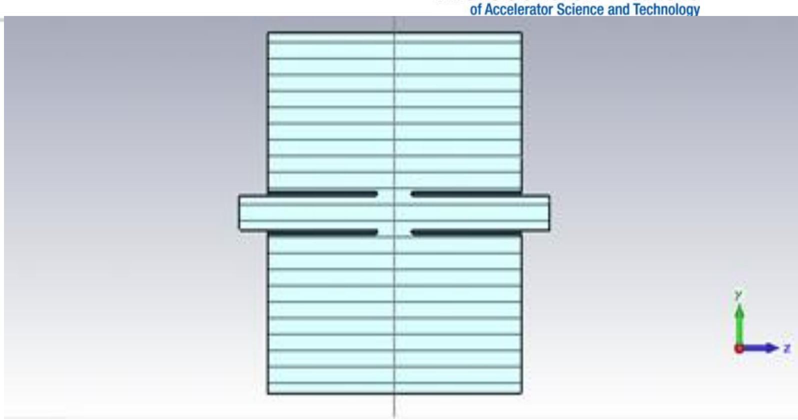
*no longer at Lancaster

Programme of Work

- Modelling of high efficiency klystrons, COM and CSM tubes (ongoing, but will move to FCC studies)
- Continue with commissioning of XBox2/3 until Ben finishes his thesis (complete but may restart)
- Testing of CLIC crab cavities (one built and tested, one being machined now)
- Design and testing of phase stabilisation setup (Phase detector built, phase shifter built, constructing experiment now)

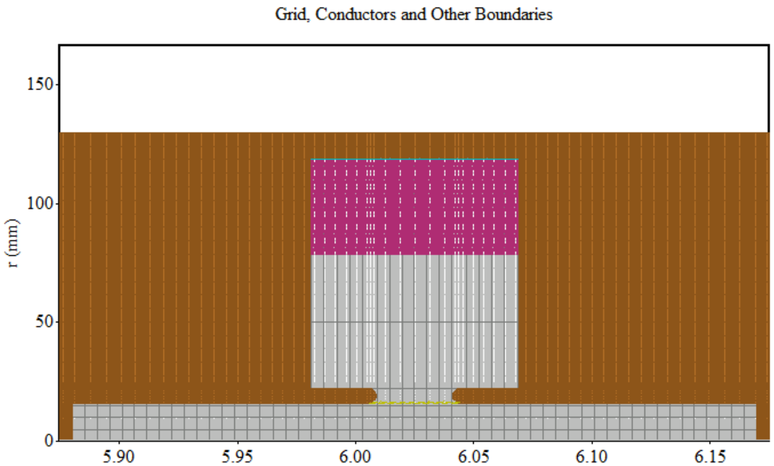
Initial HEKCW MAGIC2–D Simulations

- Initial attempts to model MBK cavities:
  - Examined in CST and MAGIC2-D.
  - Target R/Q's 352 Ohms.
  - Target Q0 ~ 10000.



- CST:
  - Allow optimiser to find geometry for required cavity parameters.
  - Highest R/Q achievable, 250 Ohms.

- MAGIC2-D:
  - MAGIC uses dielectric load with conductivity to obtain Q.
  - Attempt to 'fake' high R/Q's by also using relative permeability.
  - Results in significant decrease in maximum Q factor attainable, Q0max ~ 300.

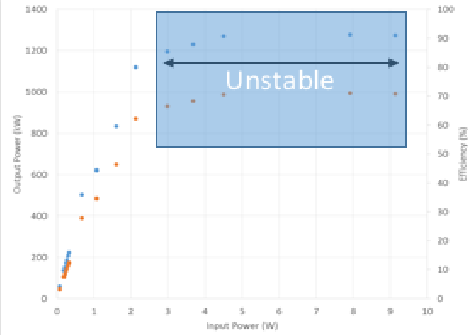


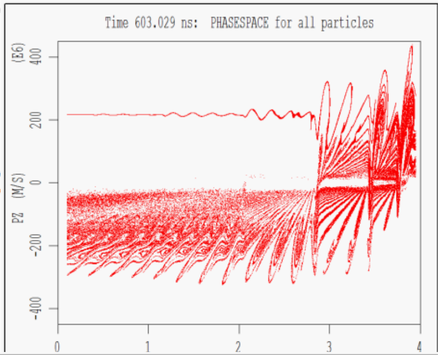
- Results here promoted move to GSP style tubes:
  - Allow attainable tubes to be modelled in 2D.

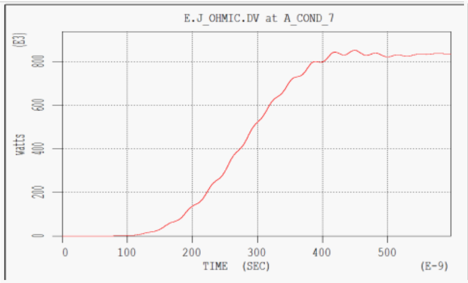
Early MAGIC2–D GSP Simulations

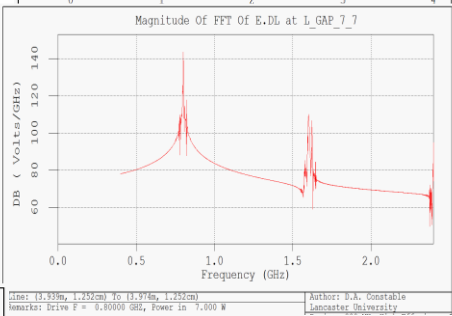
- Seven cavity, 800 MHz tube (07-02):
  - Frequencies of cavities 3-6 very close together, ~830 MHz.
  - 1-D simulations predicted high efficiency, >80%, and highlighted reflected electrons.
  - MAGIC predicted much lower efficiency, ~70%, and reflected electrons.
  - Best stable efficiency, ~60%.
  - Output FFT has mixed spectra, ~800 MHz and 840 MHz.
  - Strong beating of cavity 6 voltage – FFT shows mix of drive and 820 MHz signal.
  - During RF ramp, temporary instability generated in cavities 4-6.
  - Behaviour also observed in CST.

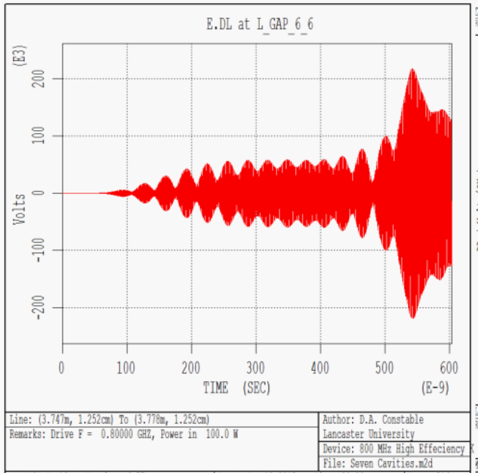
- Initially, reflected electrons from final cavity:
  - Voltage in final cavity ~ beam voltage.
  - Few electrons initially reflected, leads to avalanche, increase in cavity 6 voltage.
  - Electrons eventually reflected from cavity 6.

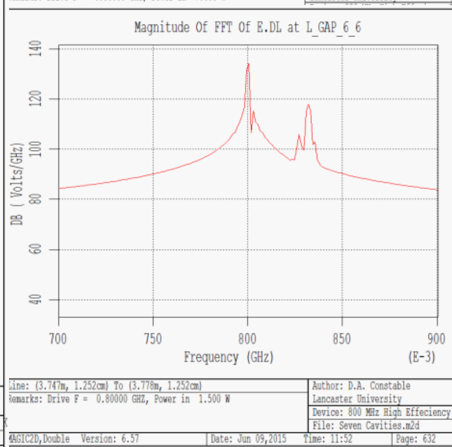






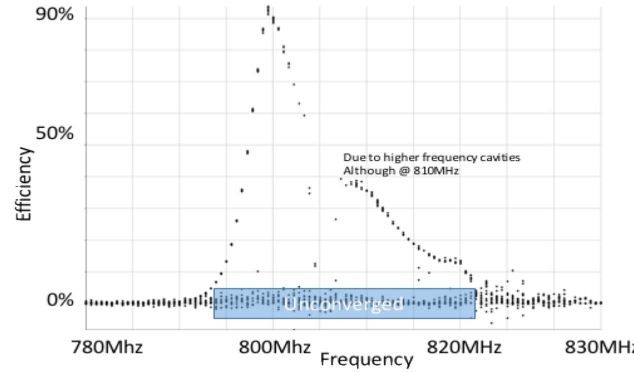


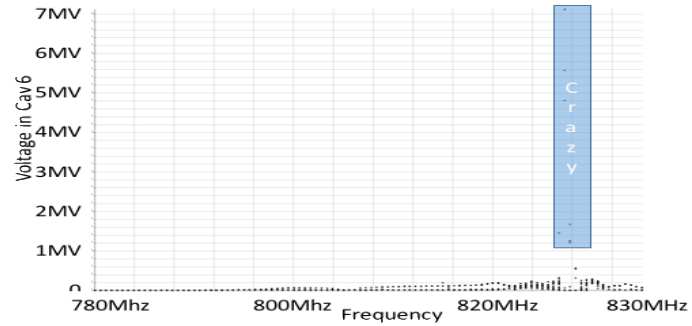


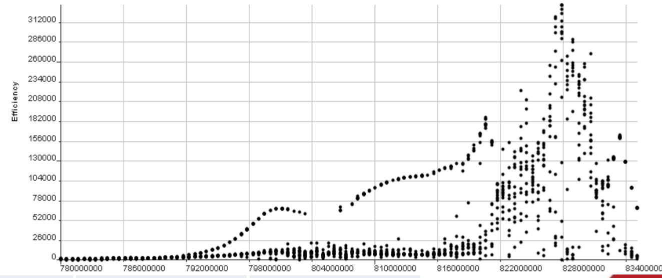


GSP 07-02 Cavity 6 AJDISK Study

- Perform examination of GSP 07-02 in AJDISK:
  - ~90% efficiency predicted at 800 MHz.
  - Q0 of intermediate cavities, 10000.
  - Reasonable efficiencies can be attained at ~810 MHz drive frequency.
  - Due to intermediate cavities, 3-6, operating at similar frequency.
- Examine cavity 6 voltages:
  - Unphysical voltages when driven at 825 MHz.
- Identification of problem with 07-02 design:
  - Close cavity frequencies result in instability – klystron within a klystron.
  - Initial attempt to resolve, reduce Q0 to 500.
  - Reduces cavity 6 voltage by an order of magnitude in AJDISK.
  - Reflected electrons still predicted in AJDISK.
  - Unstable tube still predicted in MAGIC.
  - Reflected electrons identified as primary challenge to tube development!



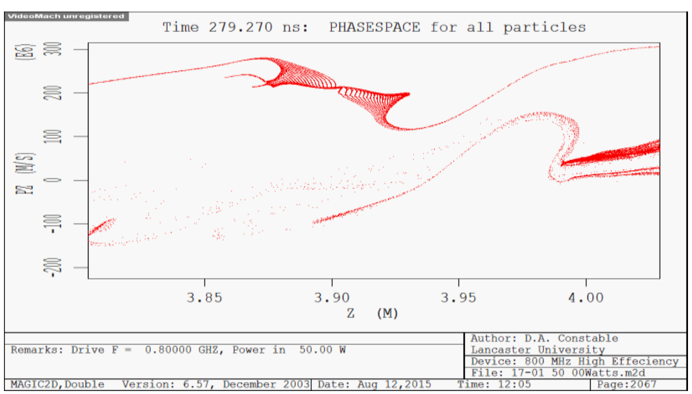


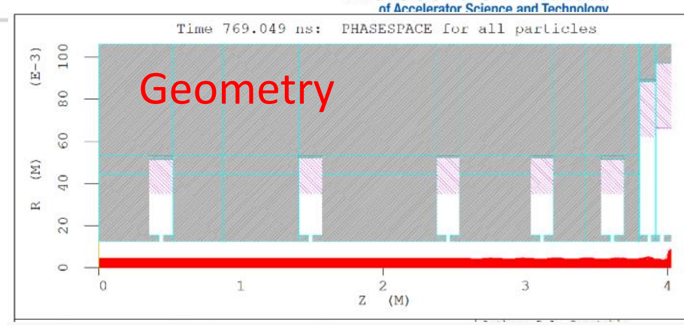


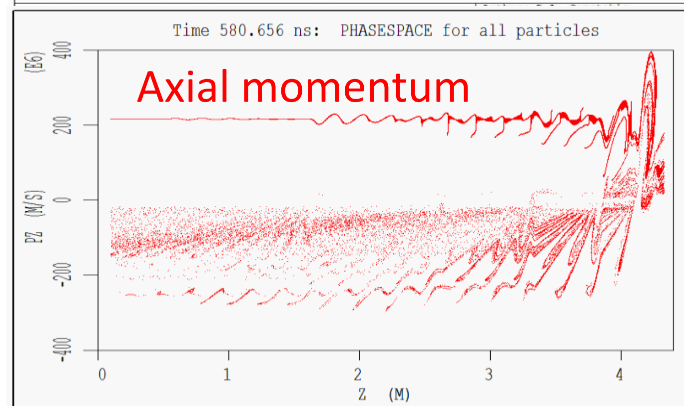
Cavity Number	1	2	3	4	5	6	7
Frequency (MHz)	801.07	805.588	826.79	825.198	829.178	827.287	794.71

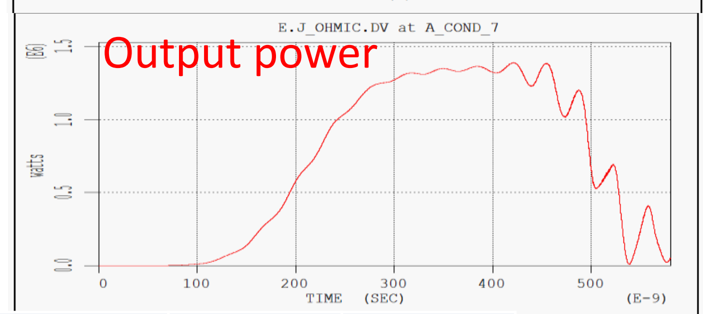
MAGIC 2-D, GSP 17-01

- Move to redesign, GSP 17-01:
  - Broader frequency span between intermediate cavity resonances.
- Promising output power, but still unstable.
  - Max stable efficiency, ~59%.
  - Reflected electrons from final cavity.
  - Tube eventually destabilizes, as seen previously.
- Also experimented with varying Qe of output cavity:
  - To reduce energy being extracted from beam.
  - Reduction in efficiency to 75%.
  - Reflected electrons still predicted.







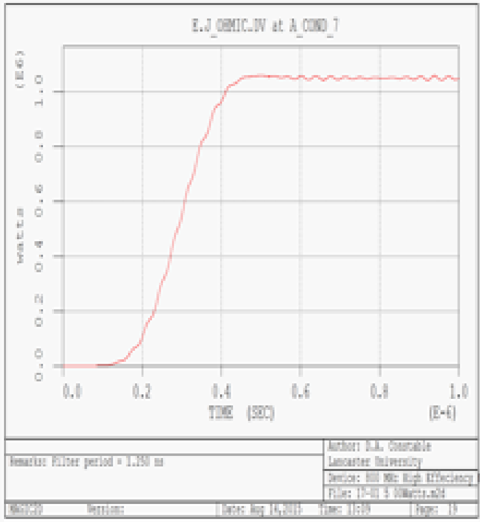


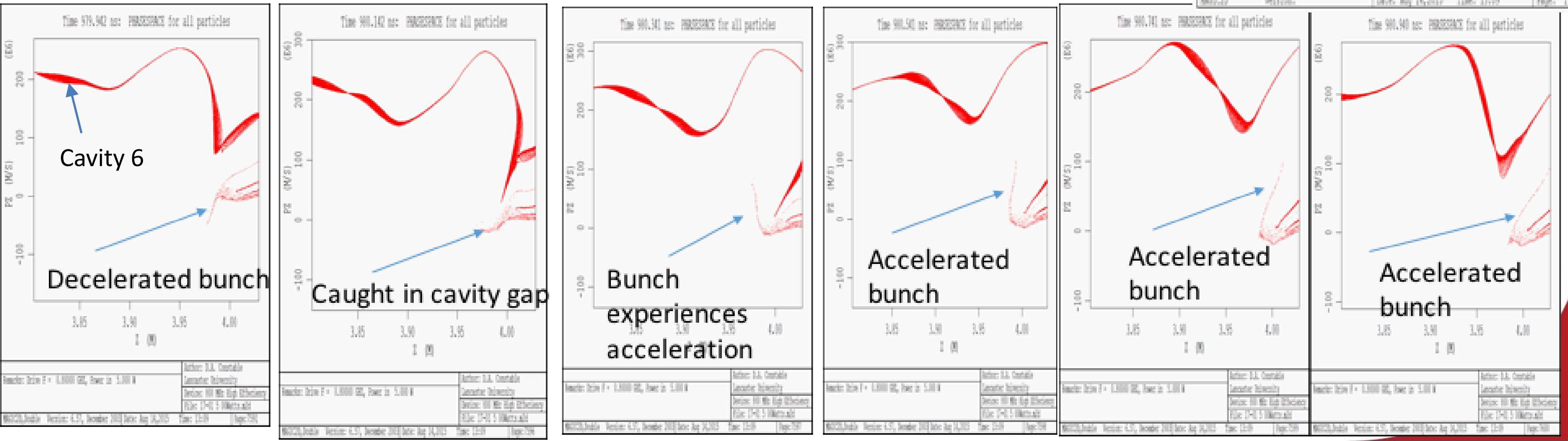
Cavity Number	1	2	3	4	5	6	7
Frequency (MHz)	785.54408	797.52176	824.4824	832.2272	828.4336	830.5816	798.3104

MAGIC 2-D, GSP 17-01 Electron Phasespace

- Electron phase space for stable situation:
  - 59% efficiency, output power, 1.05 MW.
  - Significant deceleration of electrons in output gap.
  - “Bouncing” regime of electrons.
  - Promising behaviour, as was observed in 1 GHz tube.
- Bunch entering cavity 6 is appears saturated:
  - We remove cavity 6 to examine effect (17-02).

Output Power

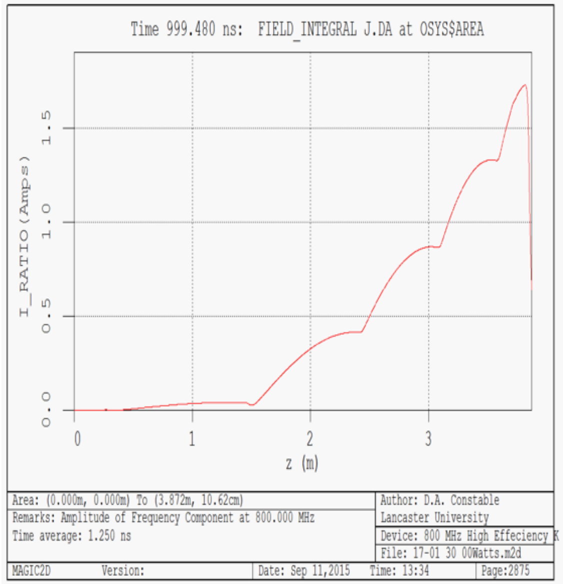


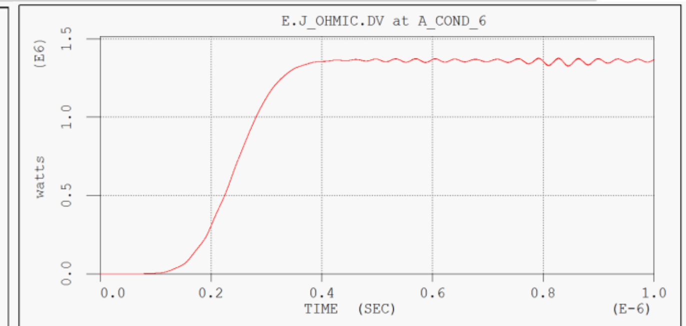


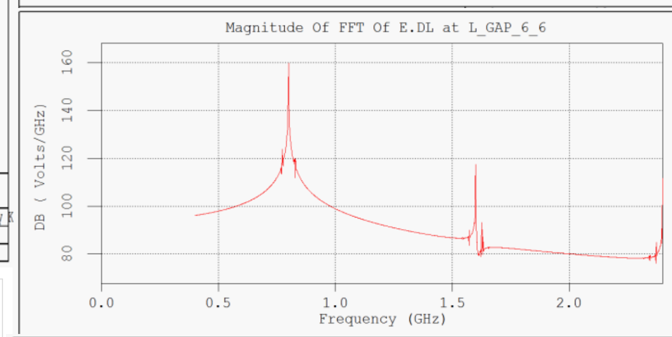
MAGIC 2-D, GSP 17-02

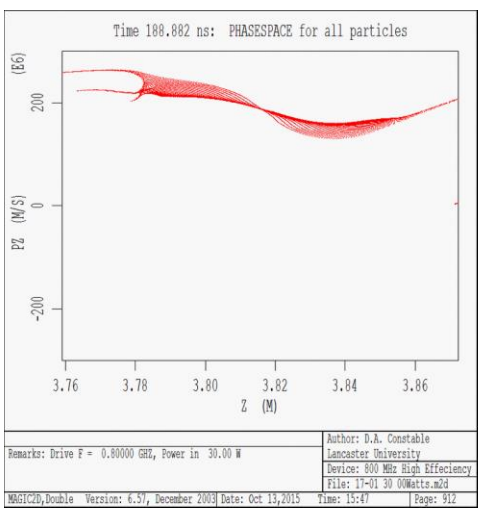
- PIC results:
  - Some reflected electrons along transfer curve, although not catastrophic.
  - Deceleration of electrons towards 0 ms^{-1} at output, before being accelerated out of gap.
  - Peak efficiency, 76%.
  - Current ratio, 1.72.

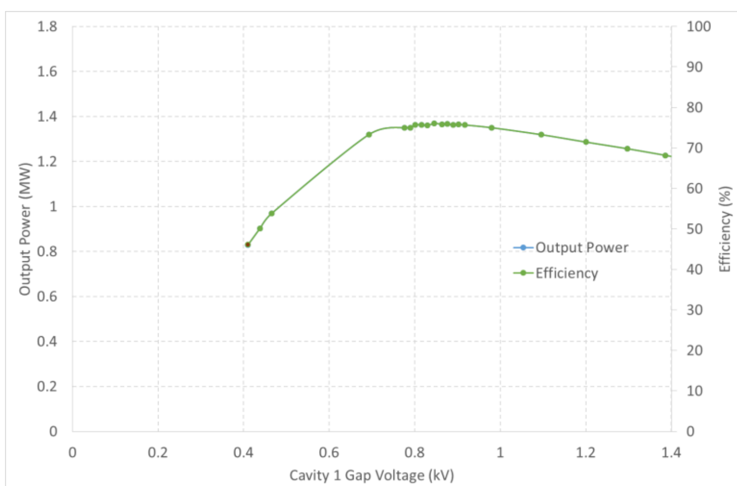
- Reflected electrons remain challenge.

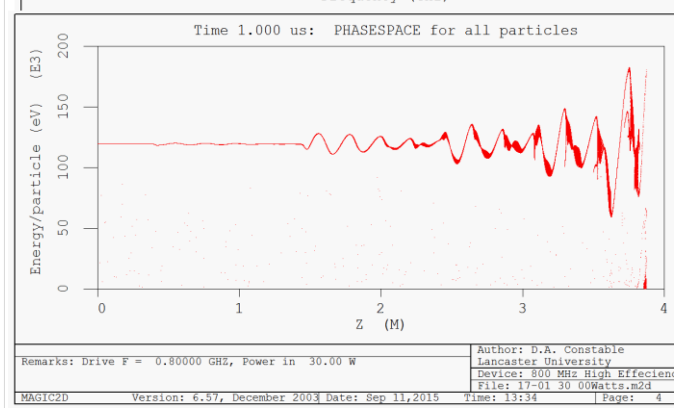












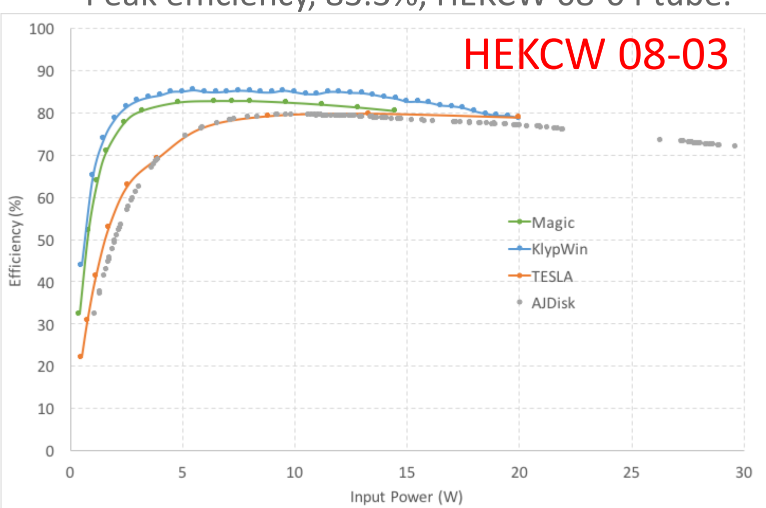
Move to HEKCW 08-Series

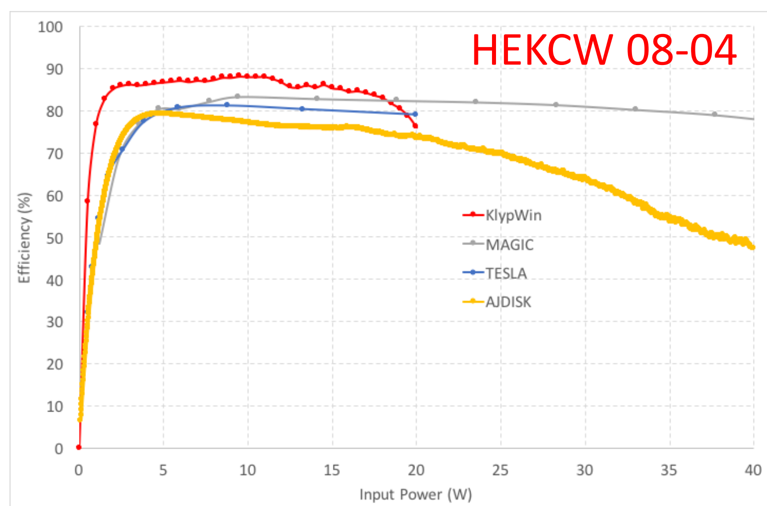
Lancaster University

The Cockcroft Institute of Accelerator Science and Technology

- Given previous results, move to 8 cavity designs of COM tubes:
  - In each case, cavity 7 has large detuning to prevent ~830 MHz issues seen in previous designs.
  - Due to reflected electrons, implementation of no overtaking electrons in optimisations from KlypWin.
  - Four tubes, 08-01 (optimised in KlypWin), 08-02 (Klys2D), 08-03 (TESLA), 08-04 (TESLA).

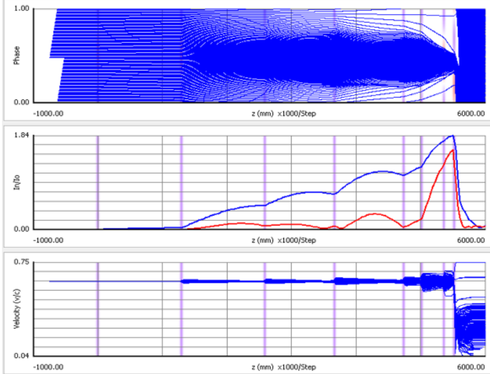
- All tubes show >79% stable efficiency in MAGIC2-D:
  - HEKCW 08-01 and 08-02 predict reflected electrons in MAGIC2-D and AJDISK with enough input power.
  - HEKCW 08-03 and 08-04 stable across entire transfer curves.
  - Peak efficiency, 83.3%, HEKCW 08-04 tube.

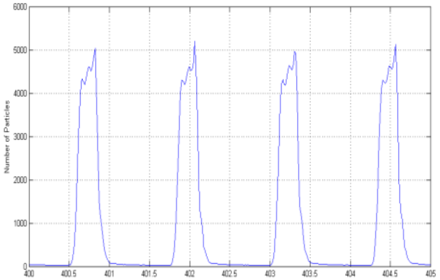


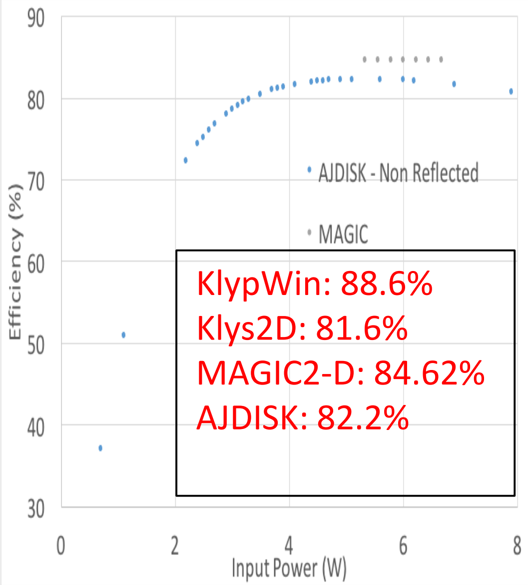


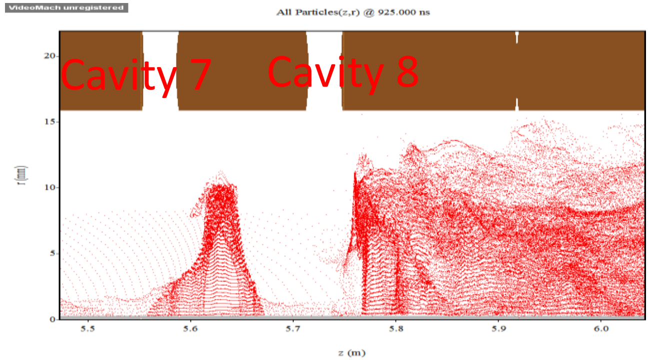
08-04-08 Results

- Refinement of 08-04 tube:
  - 1-D & 2-D modelling: KlypWin, AJDISK, Klys2D, MAGIC.
  - Number of tube iterations, frequencies, drift lengths.
  - Consistent efficiencies across HEIKA codes.
  - Tube length, ~6m; impractical at 800 MHz.
  - Stable across transfer curve.
- Radial stratification of electron bunch in PIC:
  - Bunch velocity varies with radial position.
  - Not observed in 1-D/2-D codes.
  - Electrons close to axis not affected by RF.
  - Number of particles per bunch consistent.
  - Slight variations correlate with small ripple in output.
  - Variation in particle distribution in bunch.

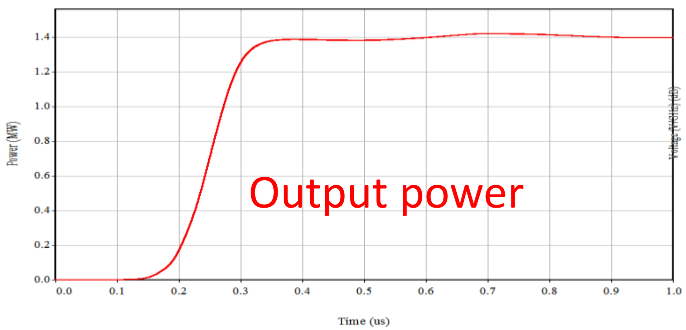


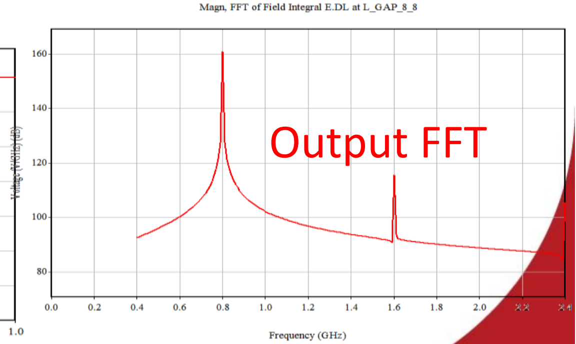






Power E.J_OHMIC.DV at A_COND_8
Step Filter period=1.250 ns

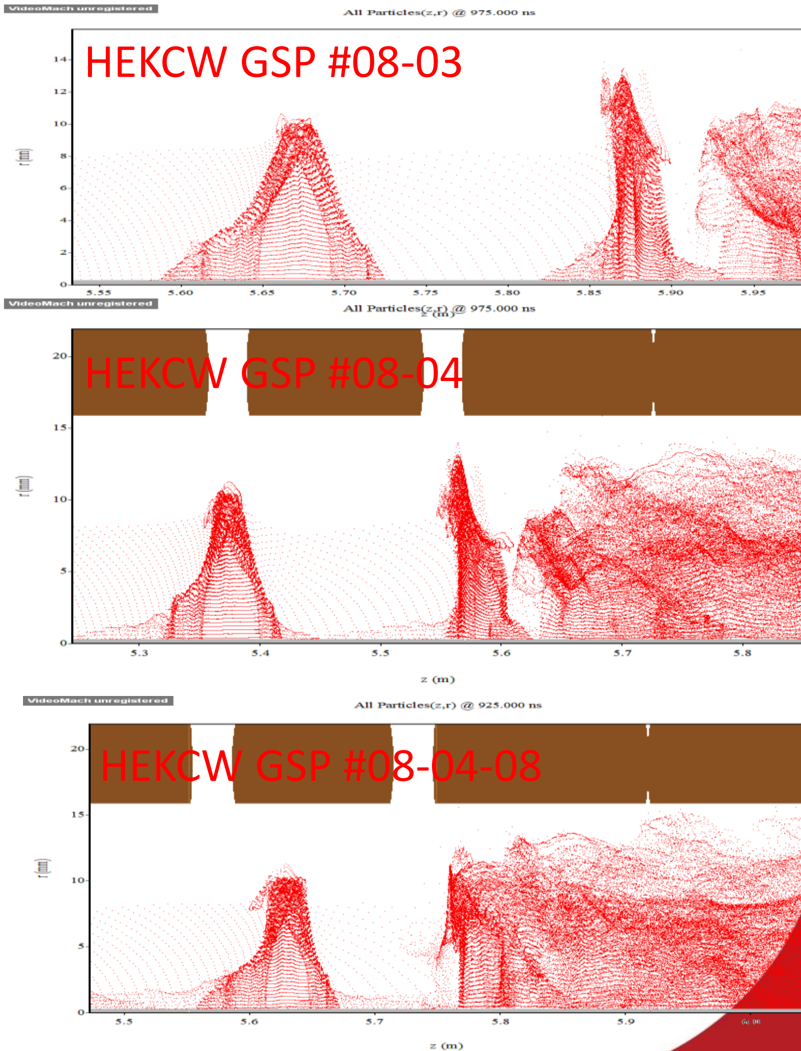




Electron Bunch Comparison

HEKCW GSP #08-03, HEKCW GSP #08-04 & HEKCW GSP #08-04-08

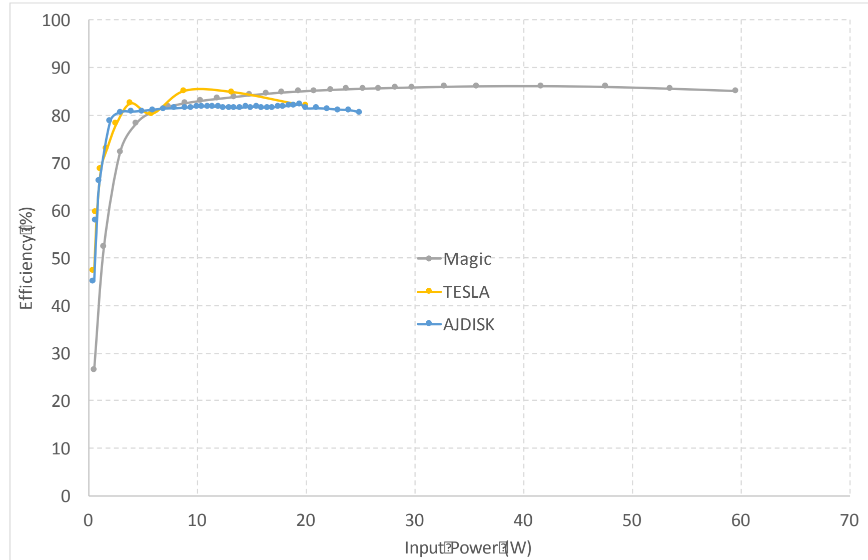
- Improvements in efficiency lie with the bunch shape at the output gap:
  - Requires the use of (at least) 2-D code in order to properly examine stratification in bunch.
- Highest stable efficiencies:
  - 08-03: 82.8%.
  - 08-04: 83.3%.
  - **08-04-08: 84.6%.**
- 08-04-08 has more slab like profile at output gap:
  - Hence, highest efficiency.
  - 08-03 has most lens shaped bunch.
  - Other tubes have more particles in the pedestal.
  - Particles on axis not affected by cavity voltages.
  - Radial stratification results.

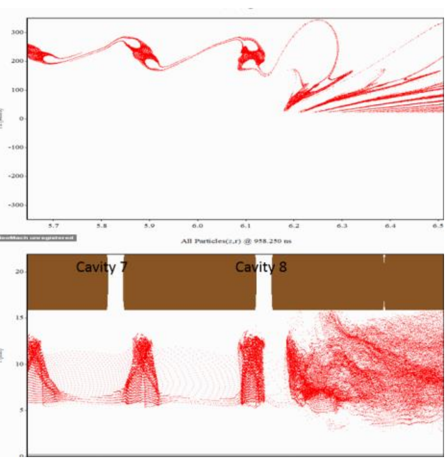


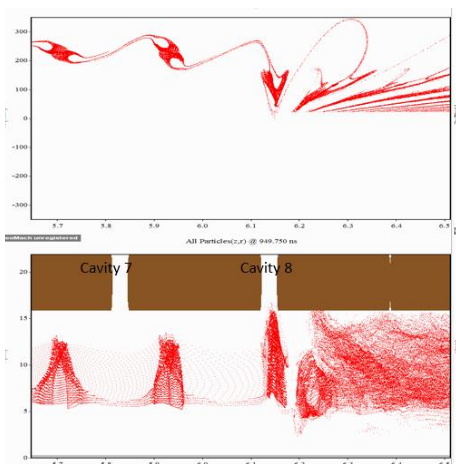
HEKCW 08H-Series

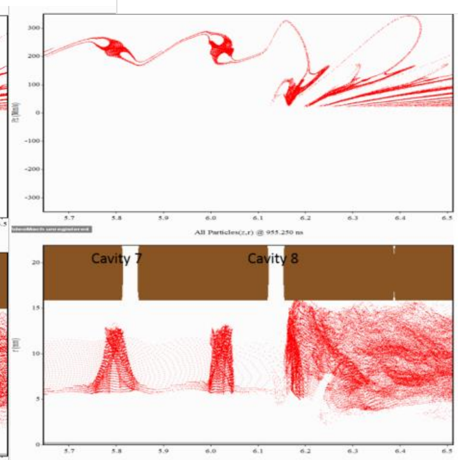
Hollow Beam, with Core Oscillation – 800 MHz

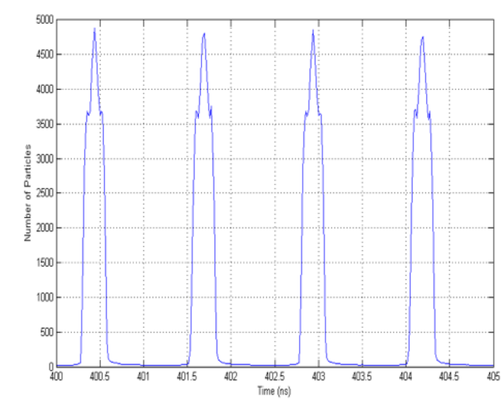
- Remove stratification effects by using a hollow beam:
  - Same operational parameters as 08-Series.
  - On axis particles removed from situation.
  - Beam density kept constant with 08-series.
  - Consistent efficiency predictions across 2-D codes, >85%.
  - Stable across all input powers.
  - Well bunched electron beam.
  - Very few particles outside of bunch.
  - Similar bunch profile between bunches.











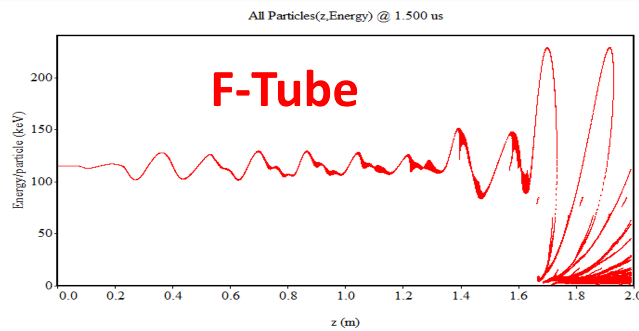
Summary of Tubes Investigated

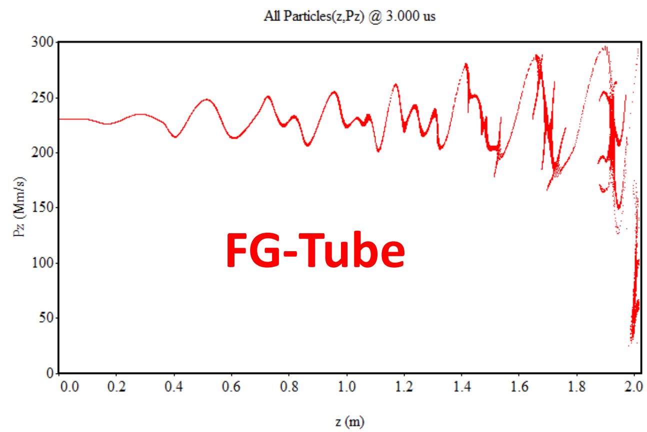
- All designs using Core Oscillation Method (COM) of bunching:
  - Scaled with GSP method.
  - Frequency, 800 MHz.
  - Investigated with 1-D disk code, AJDISK, and PIC code, MAGIC2-D.
- Initial 6 and 7 cavity designs:
  - All designs show reflected electrons in PIC.
  - Peak efficiencies lower than predicted by 1-D codes.
  - AJDISK and MAGIC simulations identified close frequencies of intermediate cavities as issue.
- HEKCW 08-Series:
  - Increased to 8 cavities.
  - Large detuning of penultimate cavity.
  - Incidence of reflected electrons significantly reduced.
  - High (and stable) efficiencies achieved.

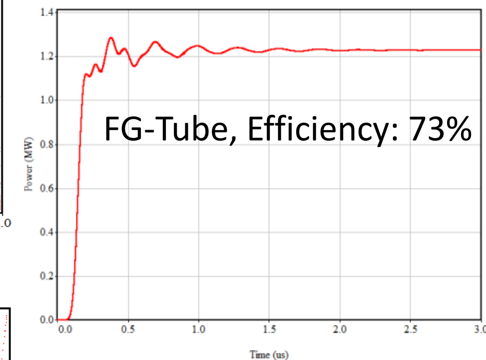
Tube Name	Number of Cavities	Maximum Efficiency	Stable in PIC?
Early Designs			
GSP 07-02	6	70	No, reflected electrons
GSP 17-01	7	72	No, reflected electrons
GSP 17-02	6	76.05	No, reflected electrons
HEKCW 08-Series			
GSP 08-01	8	80.68	No, reflected electrons
GSP 08-02	8	79.09	No, reflected electrons
GSP 08-03	8	82.77	Yes
GSP 08-04	8	83.28	Yes
HEKCW 08-04 Optimisation			
GSP 08-04-02	8	84.05	Yes
GSP 08-04-03	8	83.87	Yes
GSP 08-04-04	8	83.81	Yes
GSP 08-04-05	8	83.93	Yes
GSP 08-04-06	8	82.8	Yes
GSP 08-04-07	8	81.21	No, reflected electrons
GSP 08-04-08	8	84.62	Yes
GSP 08-04-09	8	83.45	Yes
GSP 08-04-10	8	83.99	Yes
GSP 08-04-11	8	80.06	Yes
HEKCW 08-Series Hollow			
GSP 08-H01	8	84.93	Yes
GSP 08-H02	8	86.01	Yes

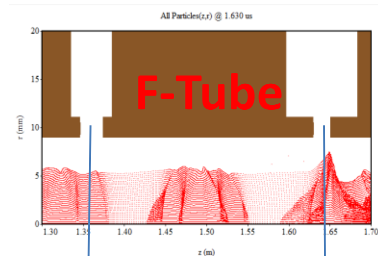
F-Tube/FG-Tube

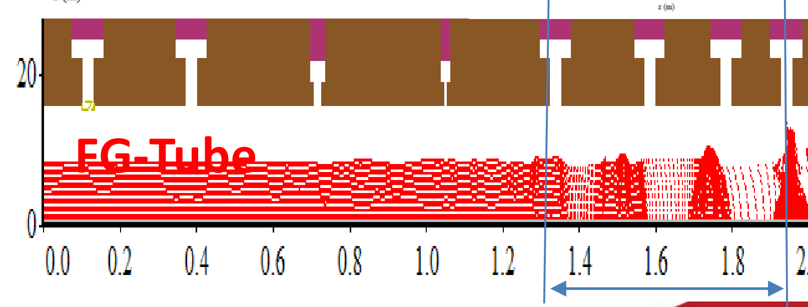
- Extension of BAC method:
  - Uses 1st, 2nd and 3rd harmonic cavities.
  - 2nd and 3rd harmonics allow collection of outsiders in reduced distance.
  - Klystrons half the length of COM tubes (~2 metres).
  - For FCC (800 MHz), 3rd harmonic cavities not difficult to construct.
  - Output power < 2 MW.
  - Designed to minimise electron phase crossover.
  - Presents "ideal" bunch at output.
- F-Tube: Original 6 cavities
- FG-Tube uses 2 additional 1st harmonic cavities.
  - Allows more gradual/gentler collection of particles.
- Early PIC results:
  - F-Tube efficiency, 80%.
  - FG-Tube efficiency, 73%.



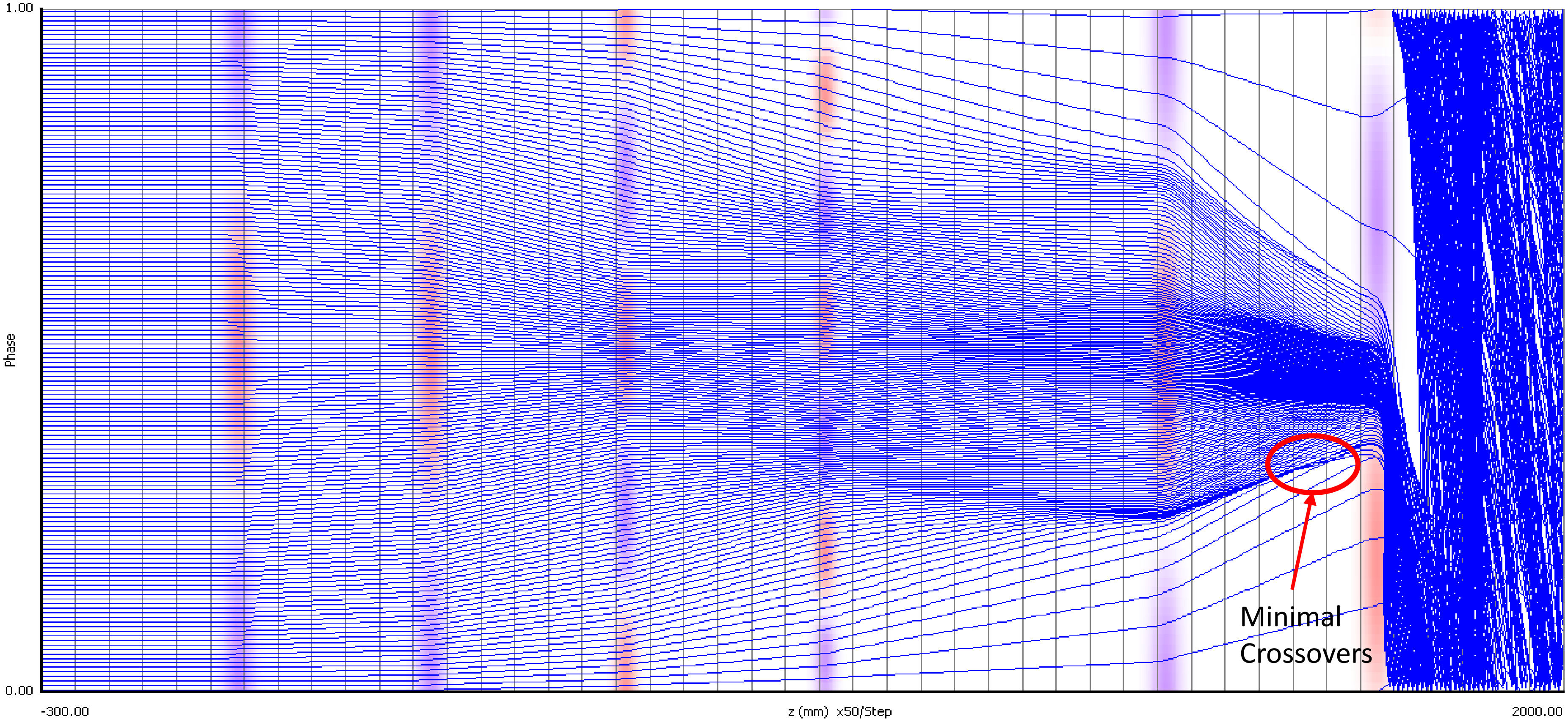






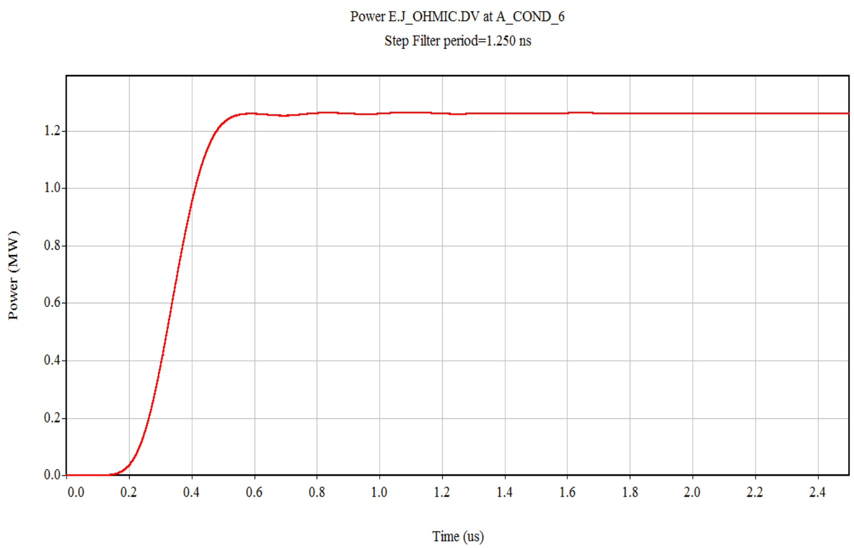


Applegate Diagram from AJDisk

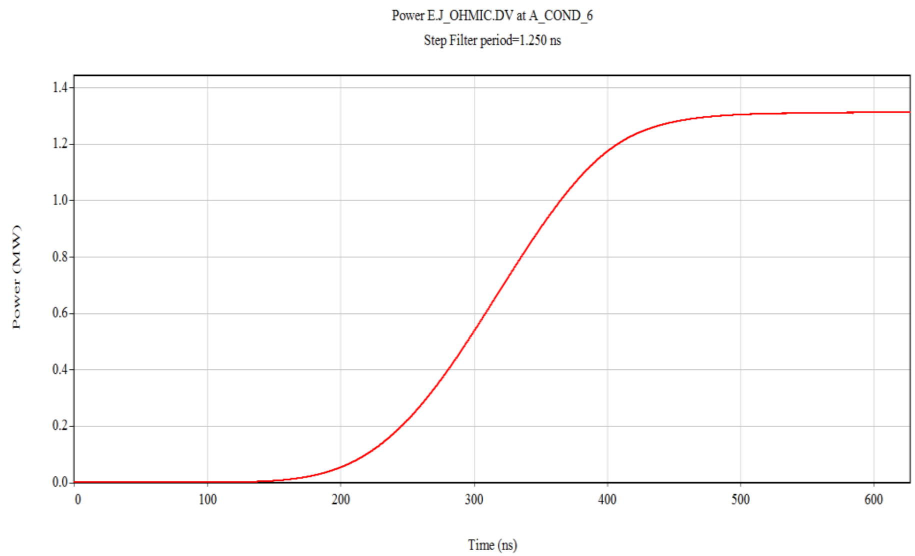


Magic Results – Output Power

- Below is the results for the input power – 60 and 90 Watts. 60 Watts to show that the tube stabiles up to 2.5us and therefore can decrease the run time of consecutive simulations just after the rise time (450ns).
- Simulations of 125 Watts and 110 Watts are currently running.
- A sweep of many different input powers will also be completed to plot a power transfer curve (once the saturation point of input power is found).

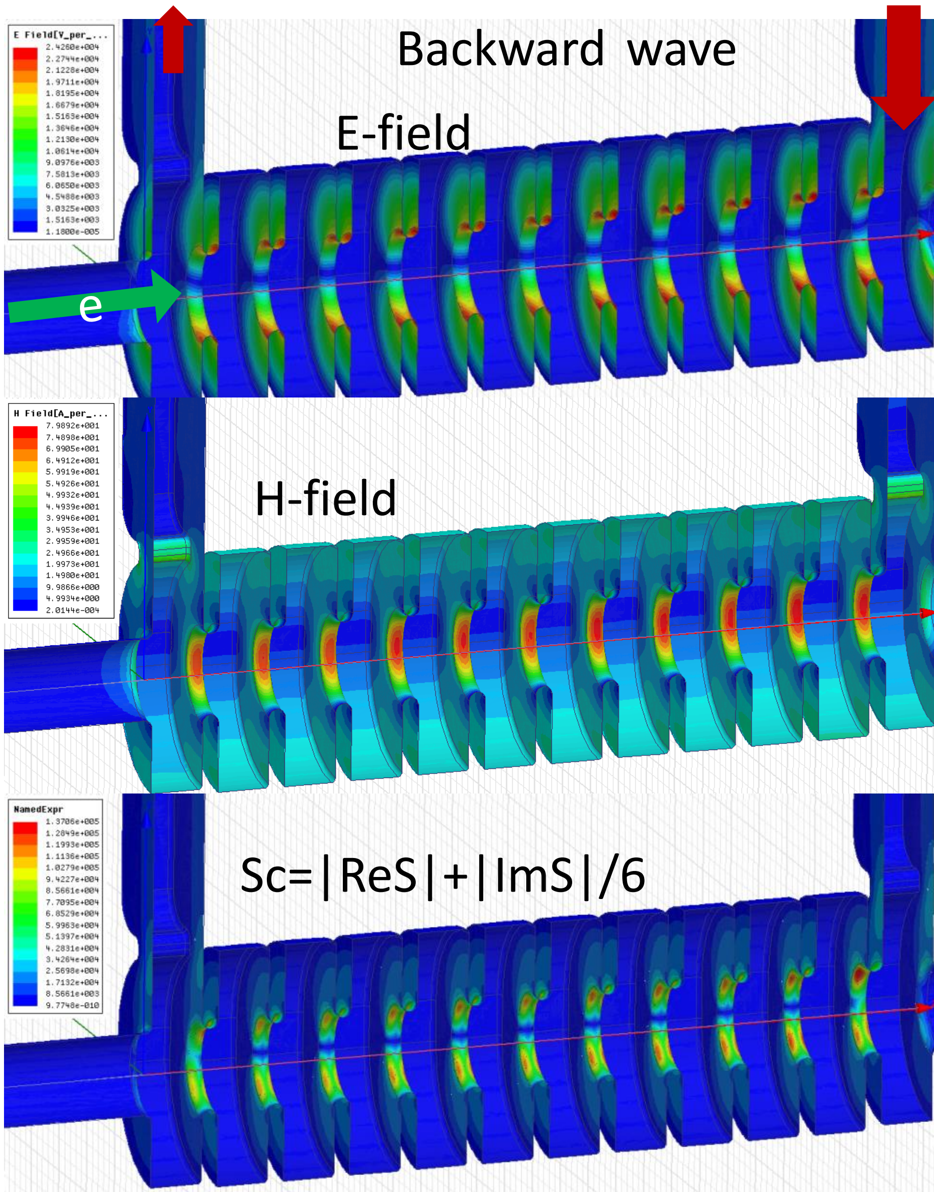


Input - 60 Watts
Output – 1.26 MW
Efficiency – 75%



Input - 90 Watts
Output – 1.339 MW
Efficiency – 78.09%

Crab Cavity Design



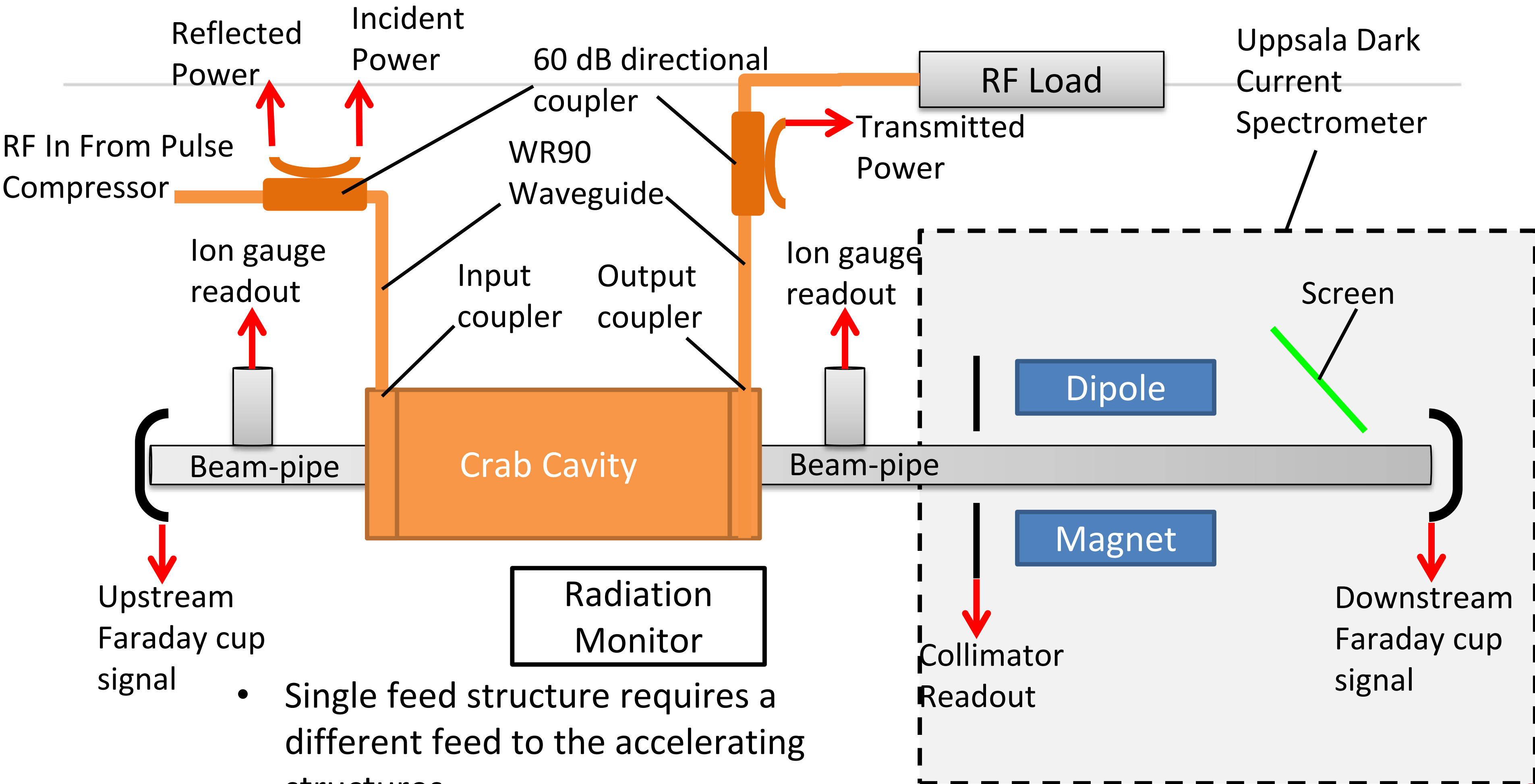
Property	CLIC T24 (unloaded)	LCLS deflector	CLIC Crab (un-damped)
Input Power	37.2 MW	20 MW	13.35 MW
Transverse Kick	-	24 MV	2.55 MV
Peak surf. E-field	219 MV/m	115 MV/m	88.8 MV/m
Peak surf. H-field	410 kA/m	405 kA/m	292 kA/m
Peak Sc [3]	3.4 MW/mm^2	-	1.83 MW/mm^2
Group Velocity	1.8-0.9%c	-3.2%c	-2.9%c
# Cells	24	117	12

Location of each surface property is different on the iris. May be able to determine which surface property causes the most breakdowns/damage using post-mortem analysis.

G. Burt

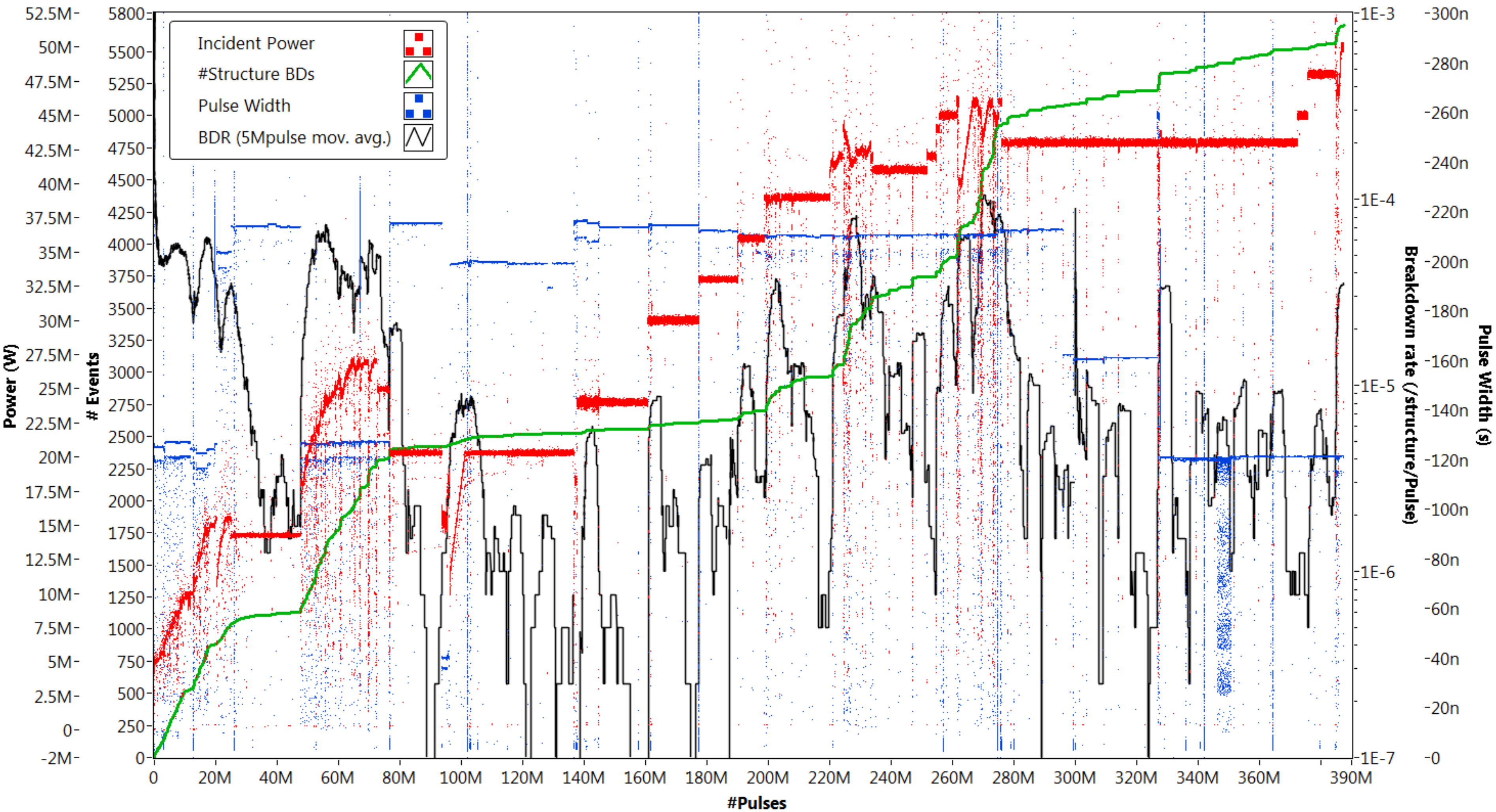
A. Grudiev V. Dolgashev P.Ambattu

Xbox-2 Diagnostics



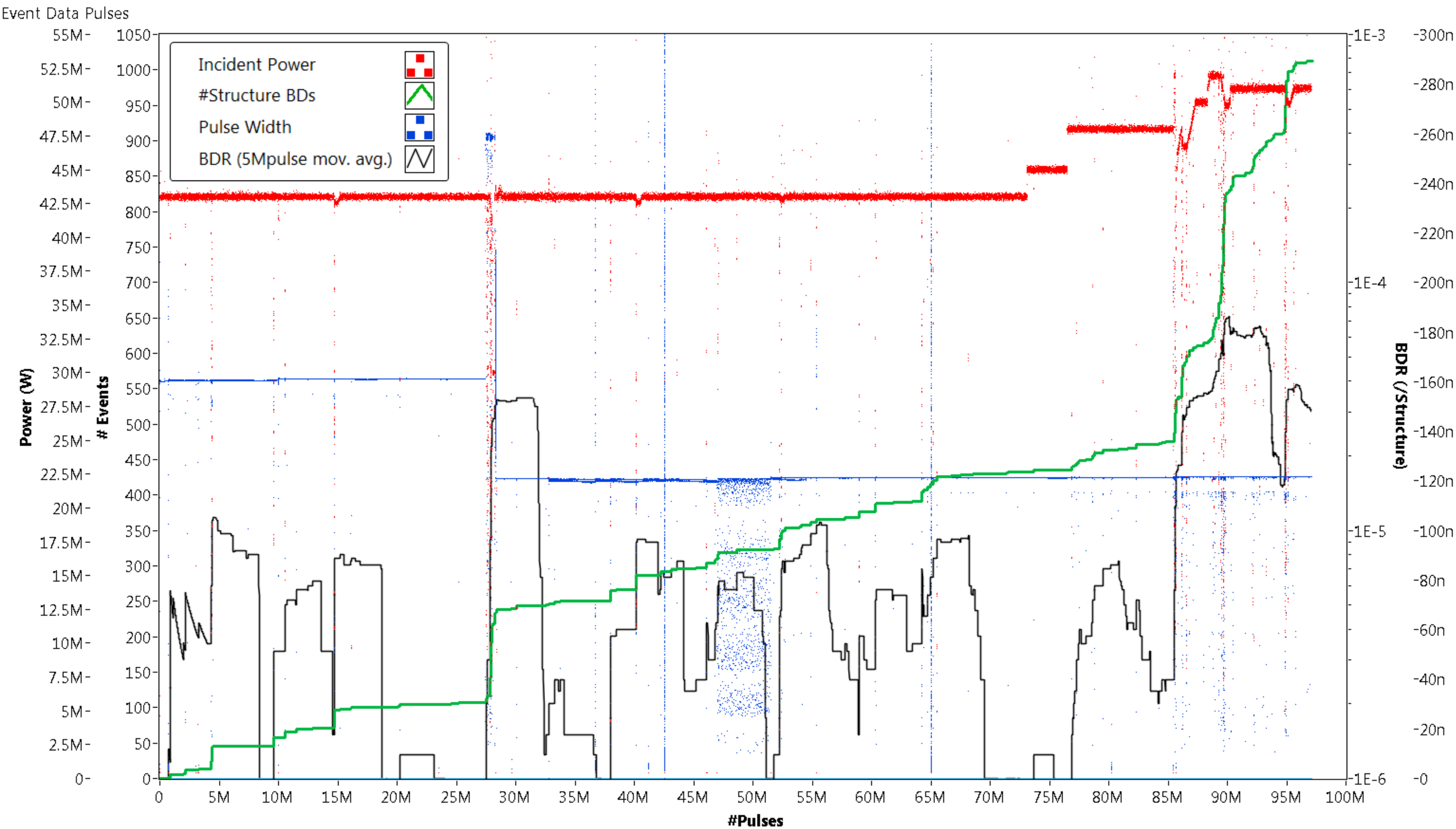
- Single feed structure requires a different feed to the accelerating structures.

Full Processing History



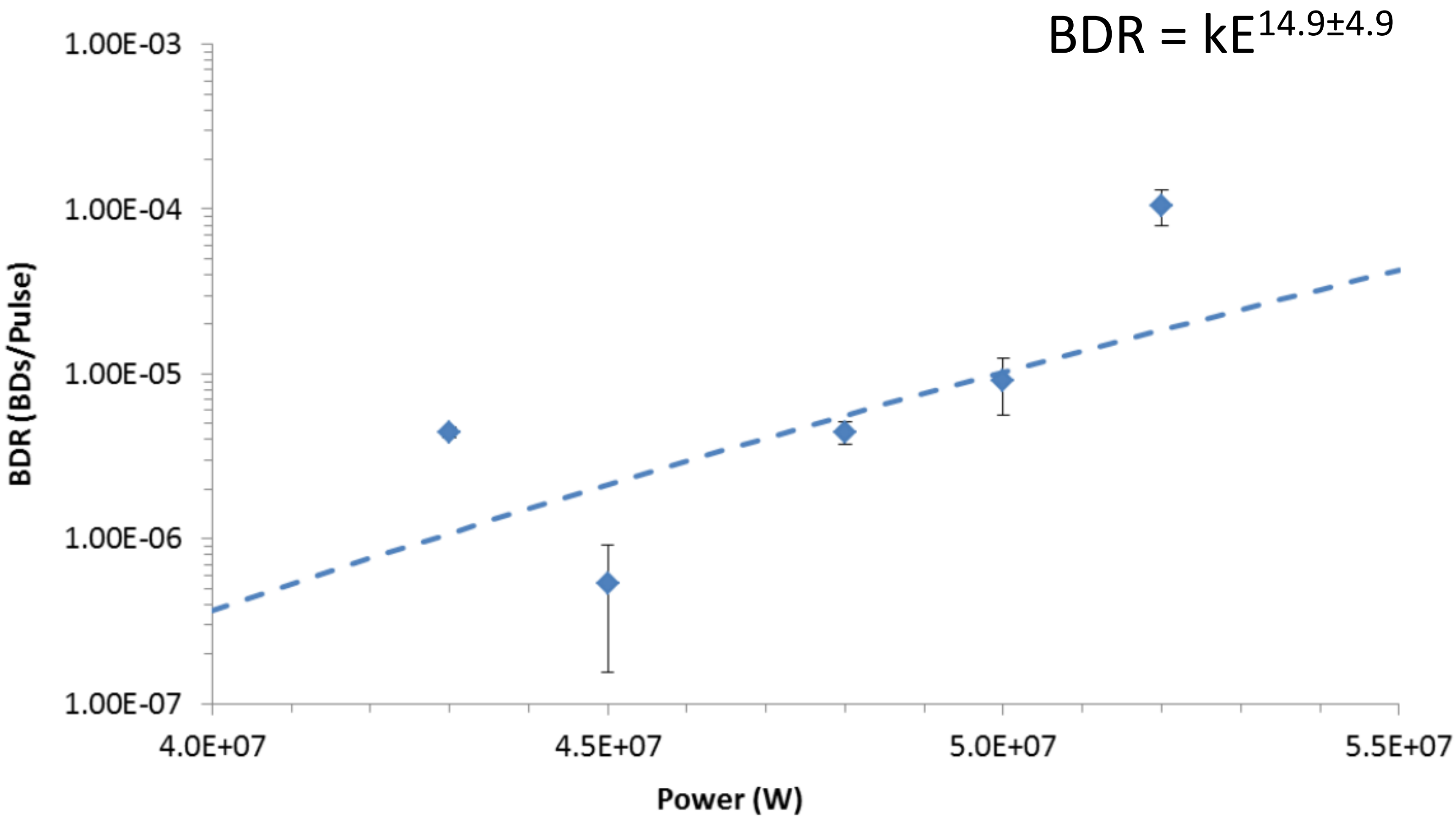
Structure has seen almost 390 million pulses with over 5700 breakdown events.
Performed well above the operating limit of 13.35 MW: **43MW, 200ns flat-top, BDR 3e-6**.
Peak power reached**: 51 MW, 100 ns flat-top, BDR 3e-5**.

Pulse width and Power Dependencies

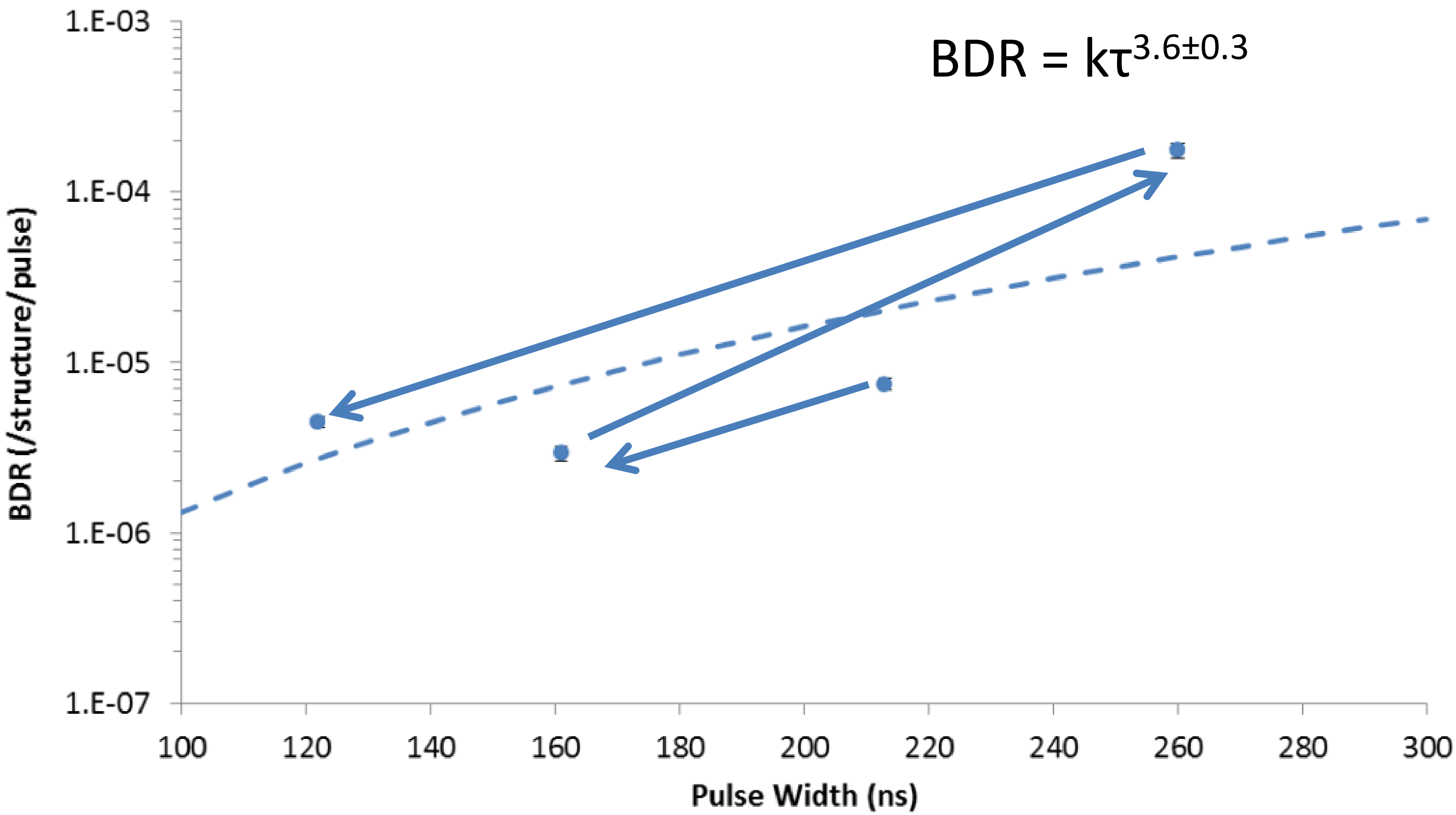


After pushing the structure to its limit at 200ns pulse width, pulse width and power level were changed to collect enough data to measure the pulse width and power dependency on the BDR.

Pulse width and Power Dependencies



Pulse width and Power Dependencies

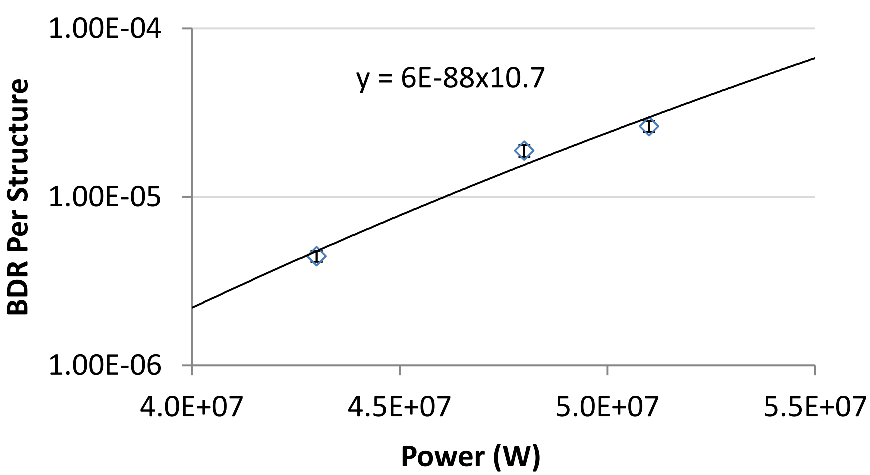


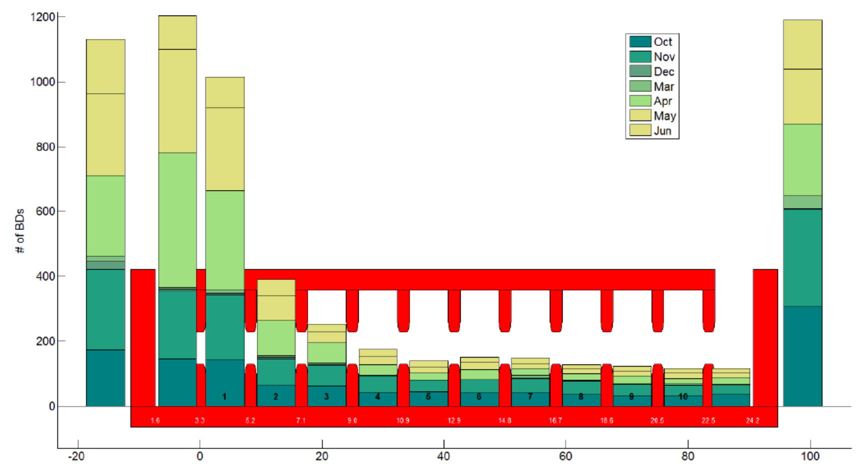
Some structure degradation occurred after running at 250 ns flat-top; the BDR for 120 ns pulse width is higher than that of 160 ns.

Power Dependencies

Property	CLIC T24 (unloaded)	LCLS deflector	CLIC Crab (un-damped)	CLIC Crab (un-damped)
Input Power	37.2 MW	20 MW	13.35 MW	40 MW
Transverse Kick	-	24 MV	2.55 MV	4.41 MV
Peak surf. E-field	219 MV/m	115 MV/m	88.8 MV/m	154 MV/m
Peak surf. H-field	410 kA/m	405 kA/m	292 kA/m	505 kA/m
Peak Sc	3.4 MW/mm^2	-	1.83 MW/mm^2	5.48 MW/mm^2
dT 200 ns	8 K	33 K	17 K	51 K
Group Velocity	1.8-0.9%c	-3.2%c	-2.9%c	-2.9%c
# Cells	24	117	12	12

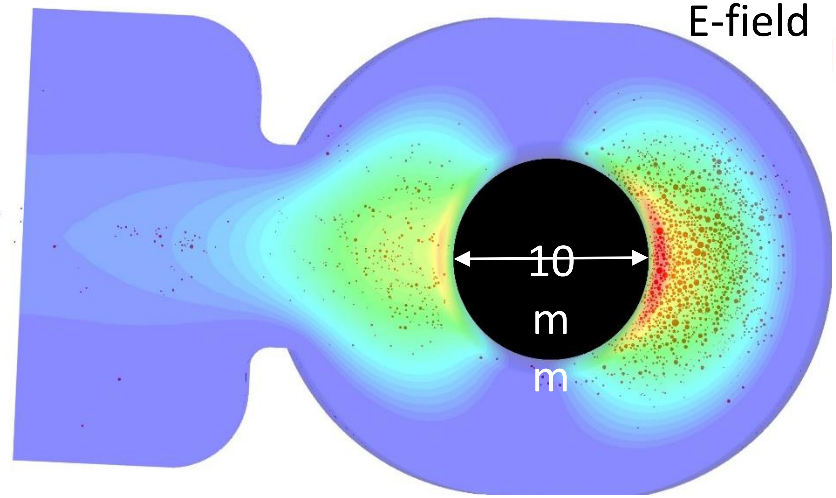
BDR Vs Power @ 126 ns FWHM



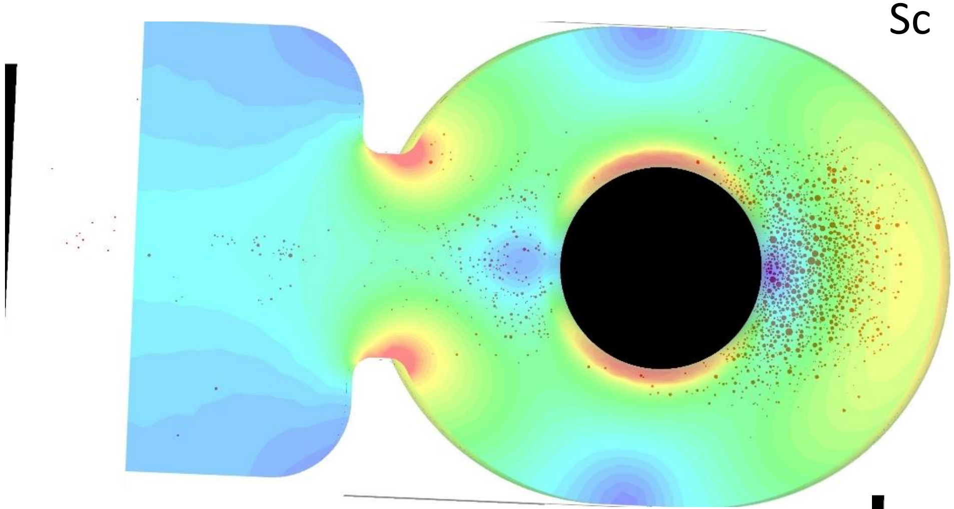


Breakdown Location

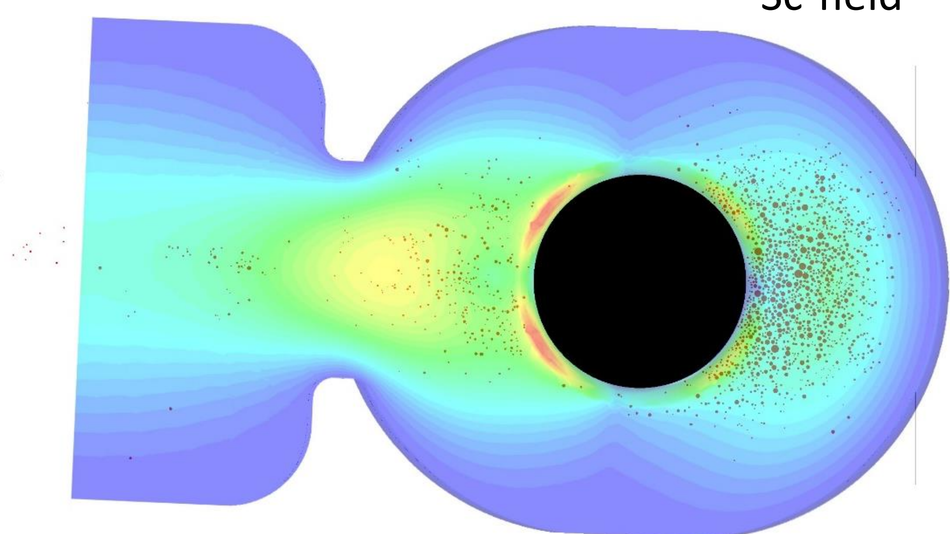
E-field



Sc



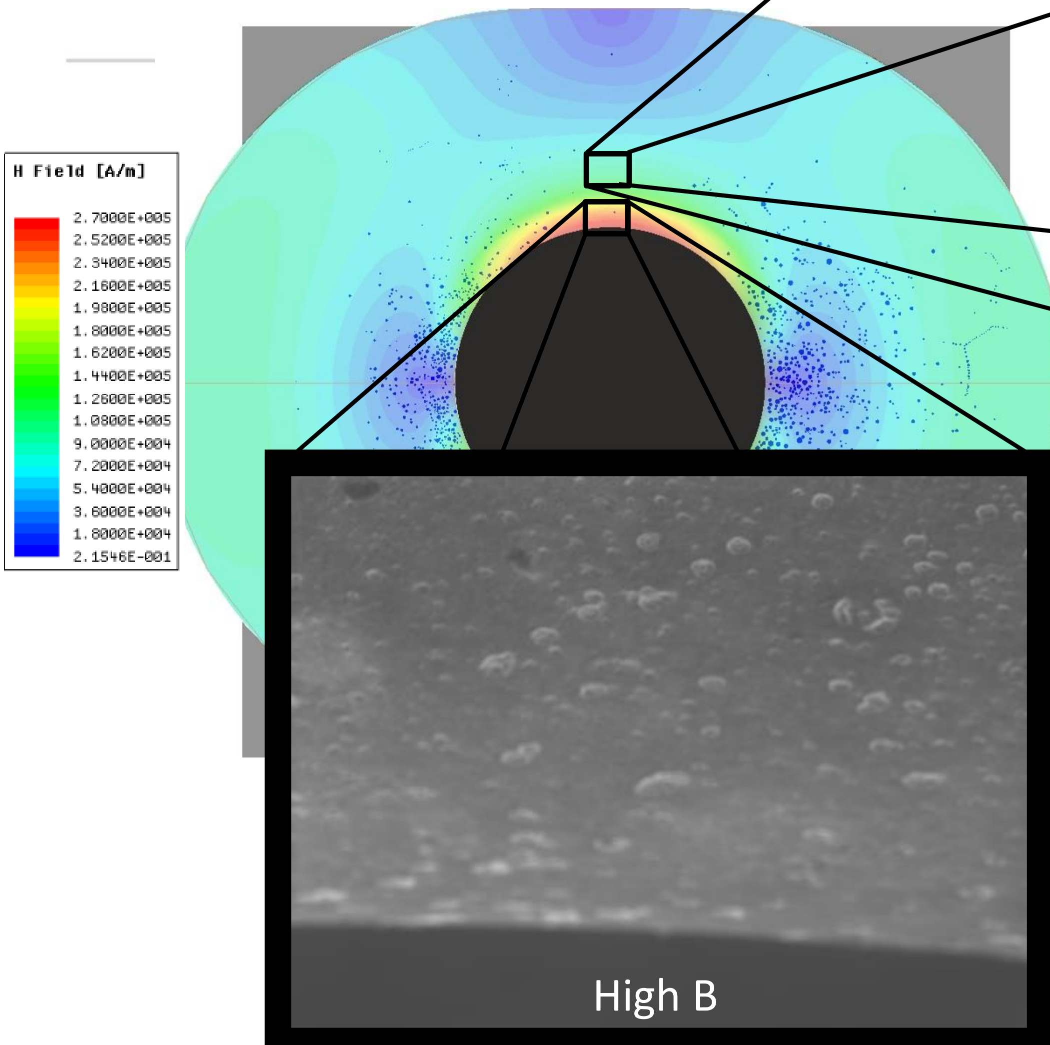
Sc-field

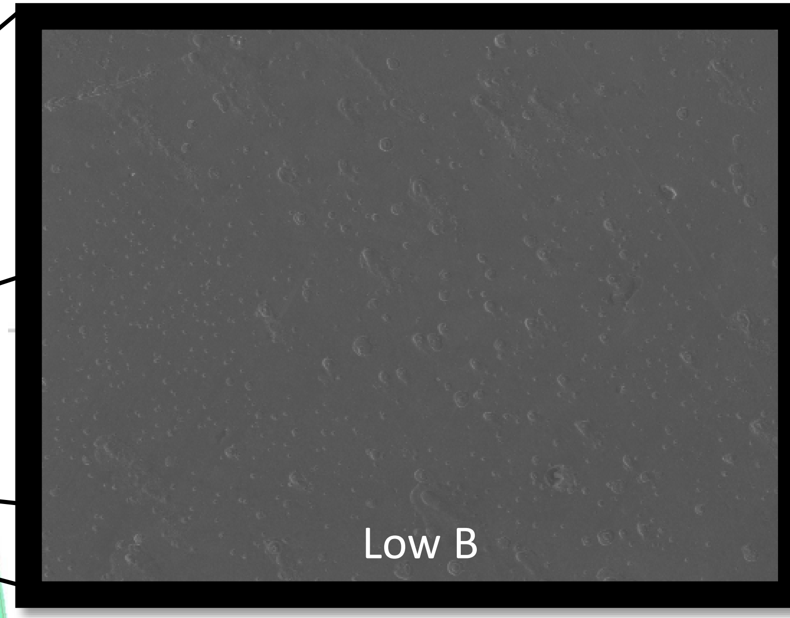


Damage location are clustered around the electric field peak, there is no correlation with pointing flux or magnetic field

This doesn’t mean the breakdown is correlated with electric field, just the damage.

B-Field Effects: Cell





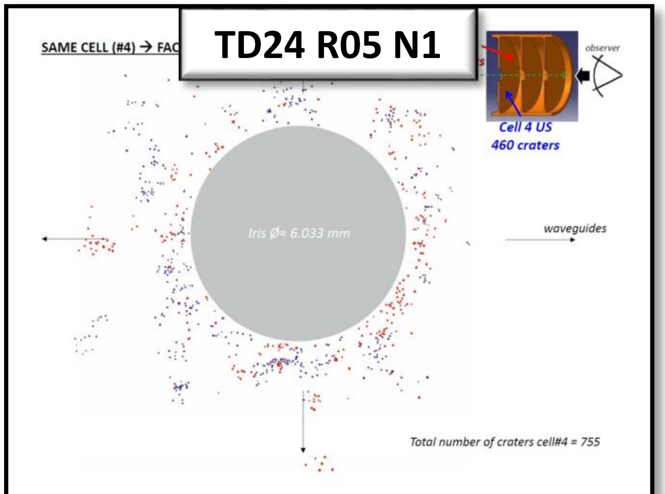
No fatigue signs in surface where the magnetic field peaks.

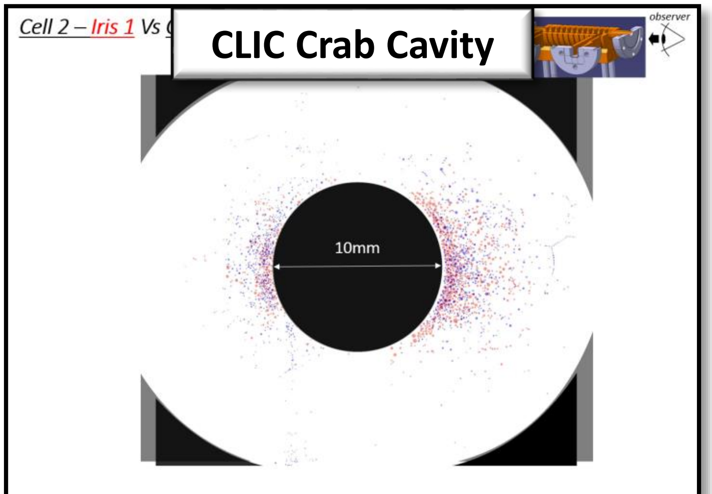
Very different from accelerating cavity results which show strong fatigue in a magnetic field.

Fatigue was shown in the coupler magnetic field.

Summary of observation

- Distribution of BDs is different than in monopole structures- follows the peak surface electric field.

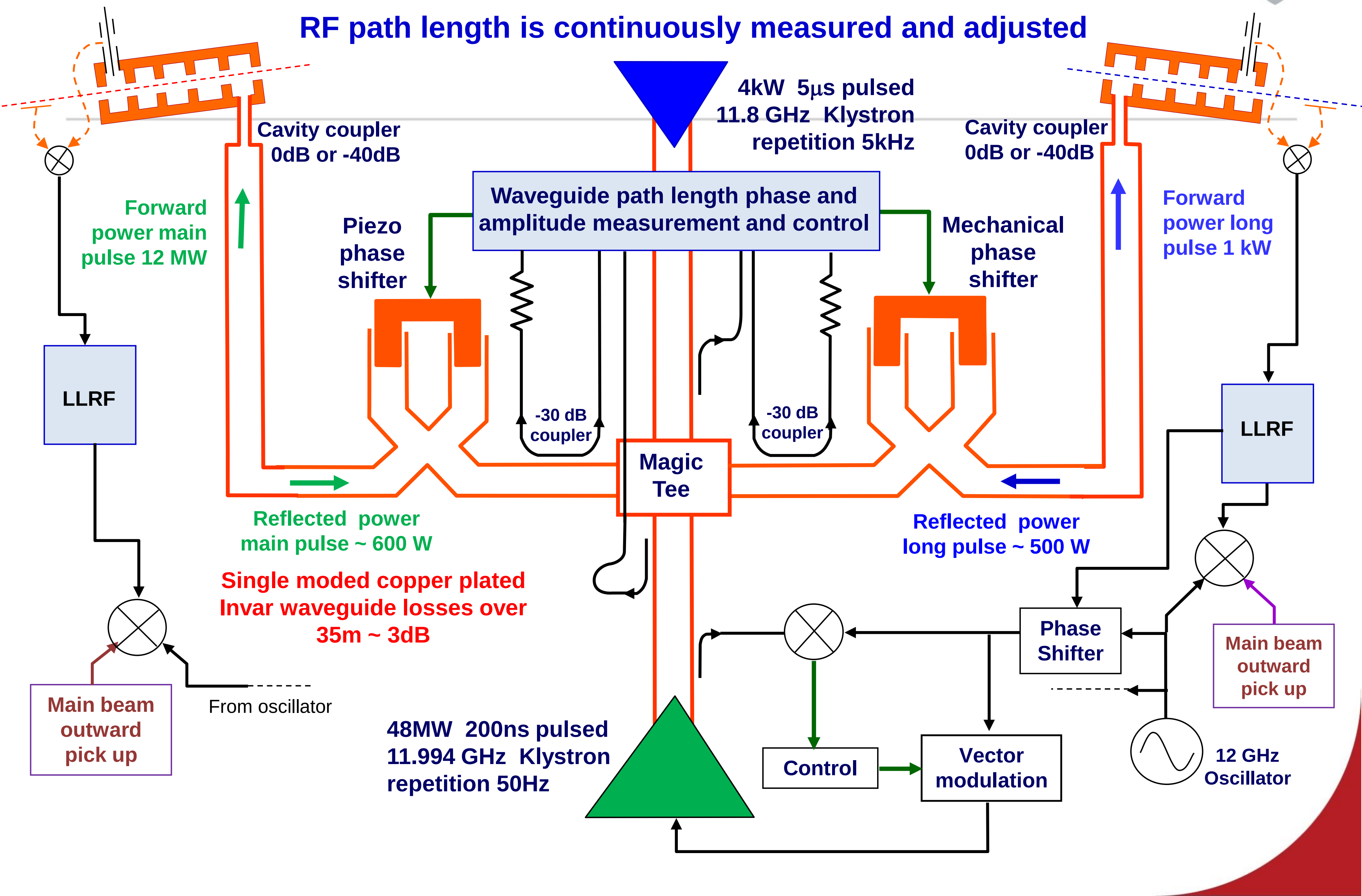




- Craters and features have same morphology that those in monopole structures
- BDs number drops significantly after firsts cells
  - To be fully confirmed with the complete observation of other cells (on going).

CLIC Synchronisation

RF path length is continuously measured and adjusted



Status Dec 2015

The PLLs under development were not quite complete before the staff member working on them left.

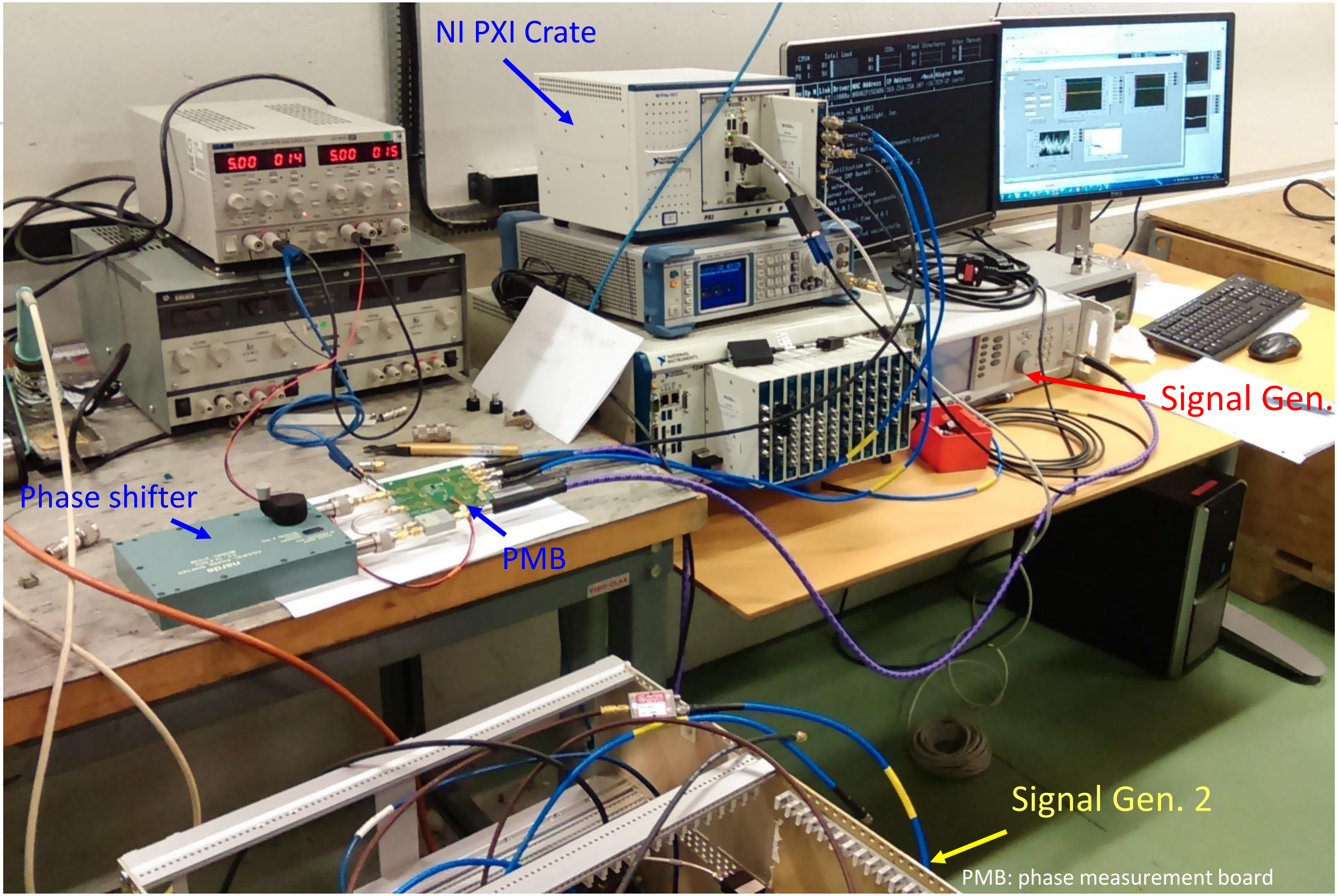
The phase board connectors had excessive reflection

Only part of the Labview code had been written

The phase shifter had not been developed

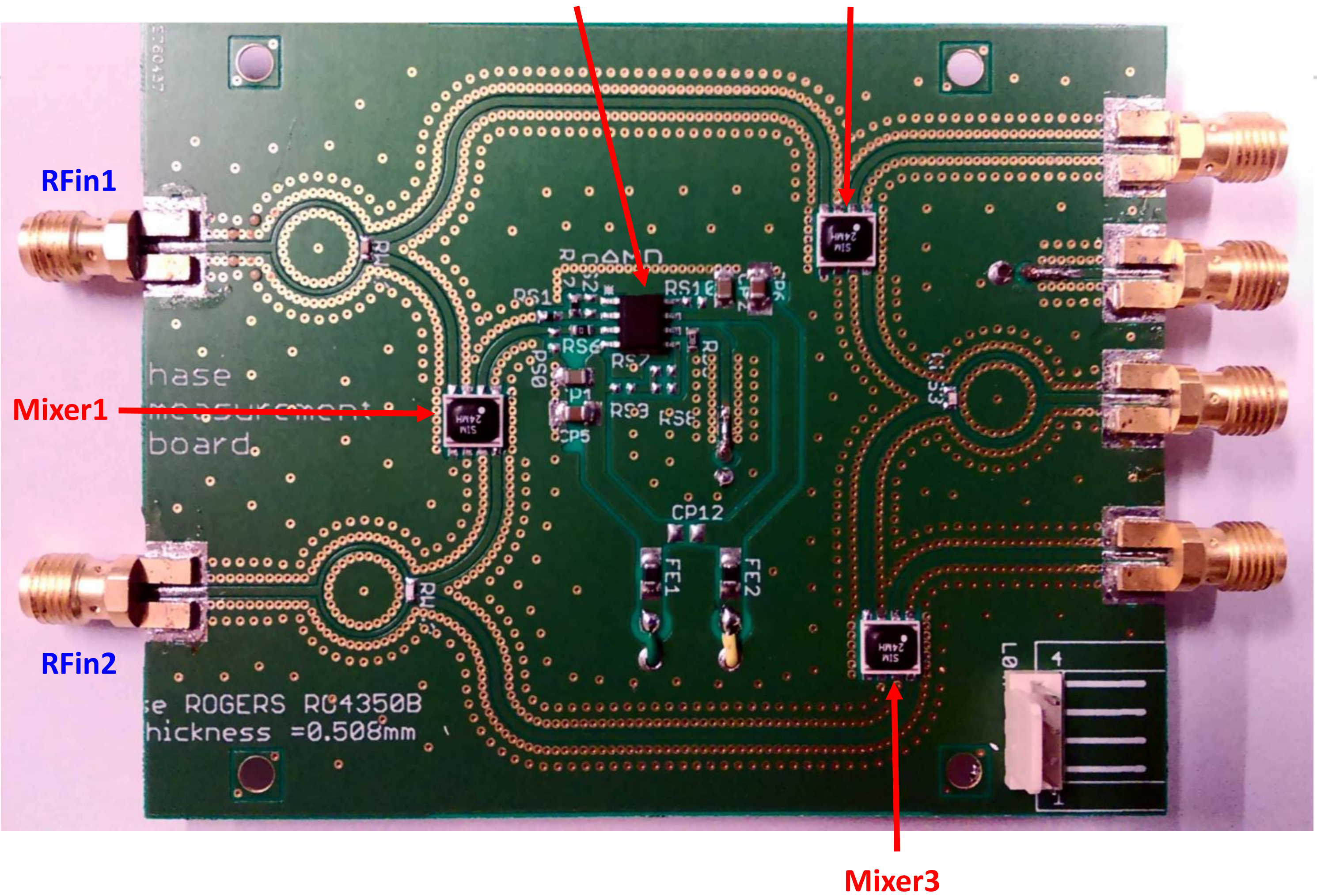
The fast switch had not been implemented

Dec 2015 Measurement

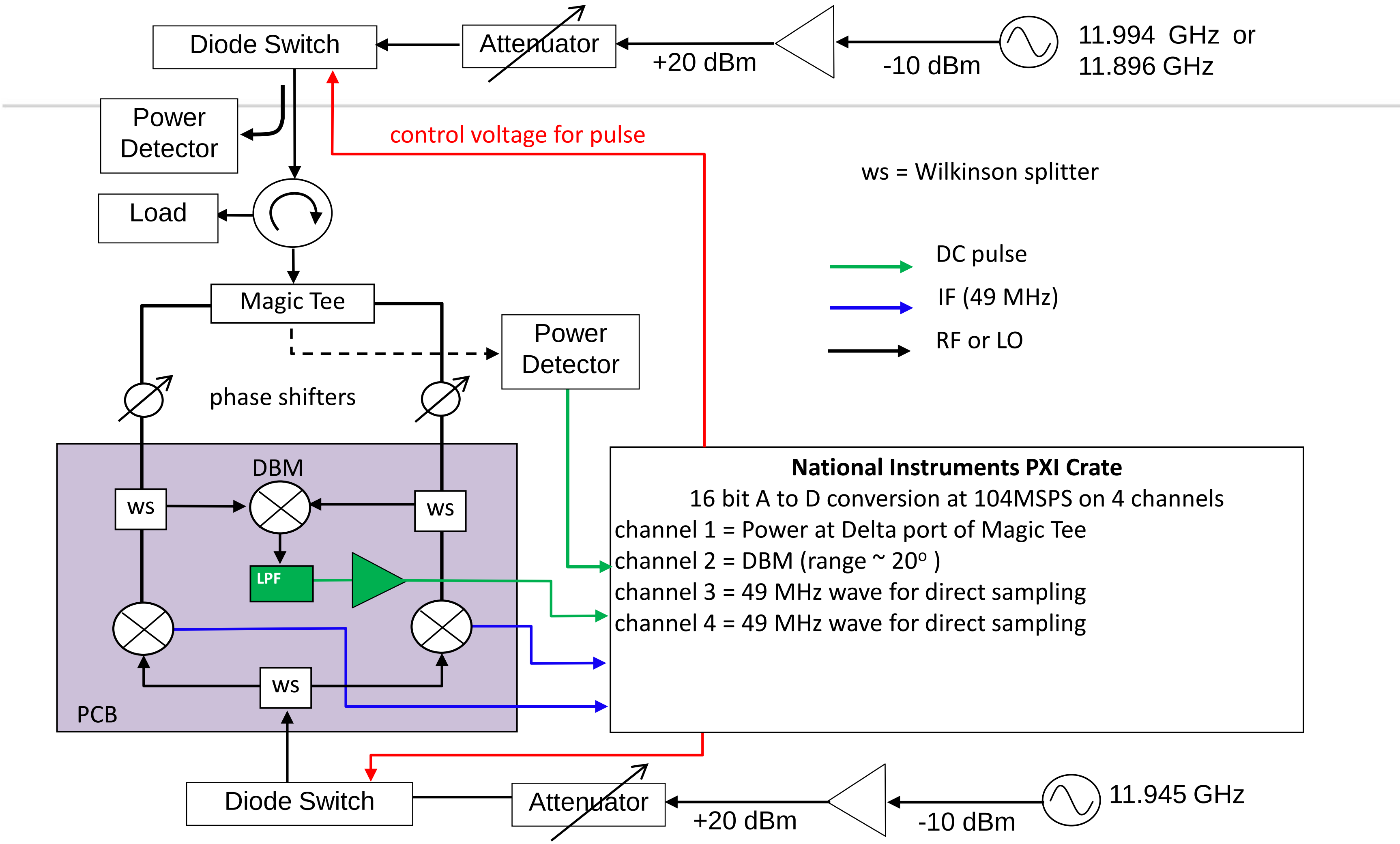


Board from 2015

DDS: Direct digital sampling



Measurement Scheme



Progress 2016

1. Piezo activated phase shifter developed
2. Fast switch implemented required for measuring offsets
3. Two commercial DS programmable signal generators have been acquired.
4. EM simulations of the phase board connector allow new PCB design with better matching
5. New boards made and implemented
6. Full measurement system has been set up and power levels optimised.
7. Labview asynchronous sampling code developed
8. Labview logging code developed
9. Auto calibration under development

New Board 2016

DDS: Direct digital sampling

Amplifier

Mixer2

IFout1

RFin1

DCout

Mixer1

LOin

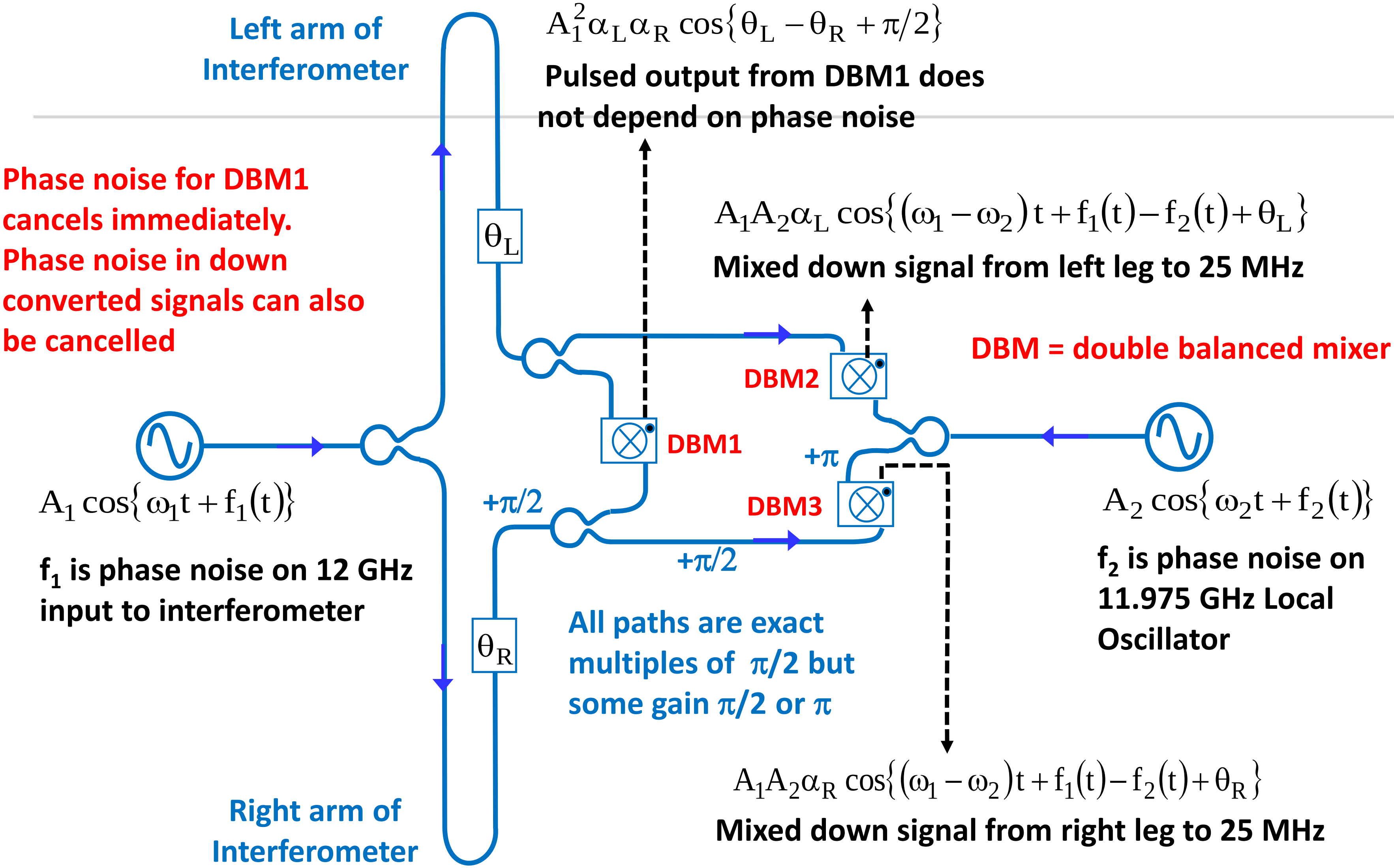
IFout2

RFin2

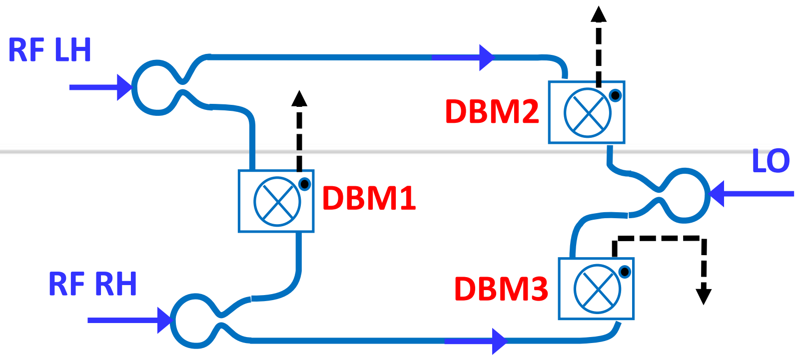
Mixer3

Signals with Phase Noise

Lancaster University



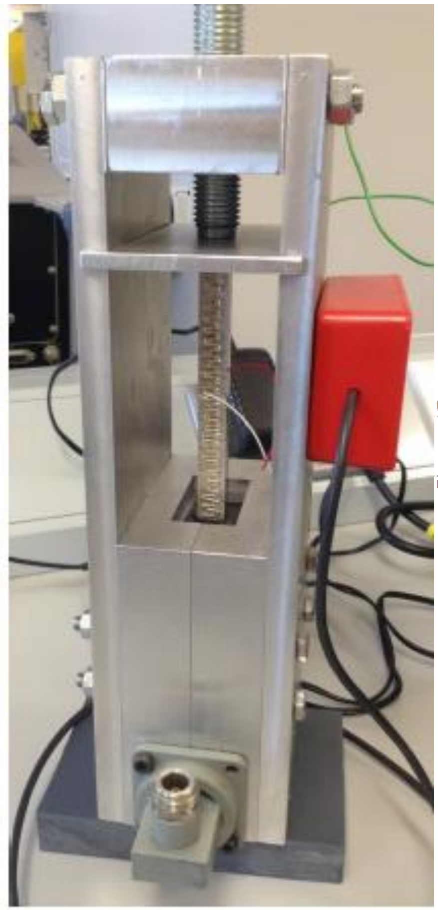
Notes on Synchronisation

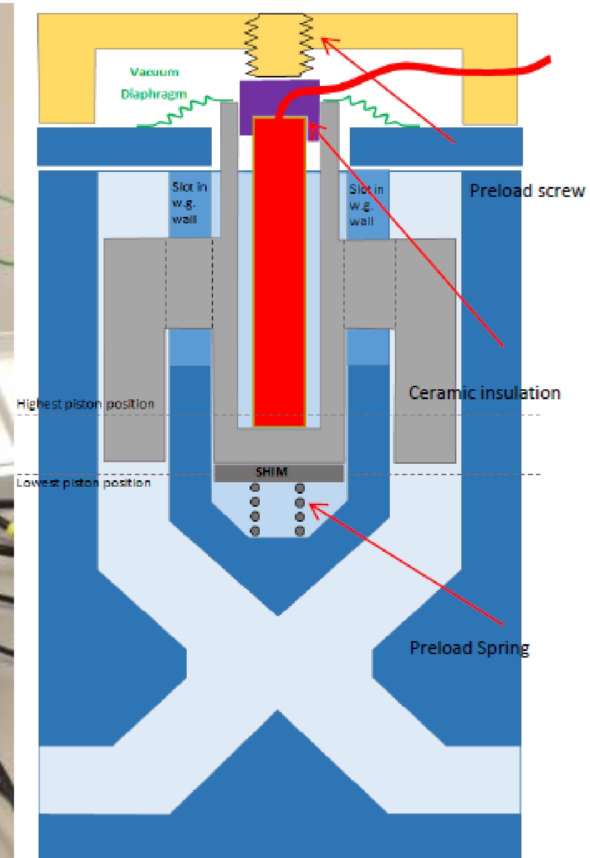


- For synchronisation DBM1 controlled to zero.
- Measurement independent of oscillator phase noise .
- Synchronisation does not require amplitude to be known.
- Very small ‘d.c.’ voltage pulses lasting the length of the RF pulse must be measured.
- Offsets can be determined between pulses and then removed.
- High amplification on DBM1 means that 360° can not be measured.
- Direct sampling of DBM2 and DBM3 allows:-
  - 360° to be determined
  - course phase variation on each arm to be monitored
  - phase differences to be brought to range of DBM1
  - calibration of DBM1 output
  - monitoring separate arms of interferometer needs RF and LO to be locked

High power phase shifter

- Prototype high power phase shifter has been produced in aluminium based on A. Grudiev’s compact hybrid.





Future activities

Discussion with Walter have narrowed down our continued activity on

- Phase stabilisation, synchronisation and measurement (main linac)
- Development of high power X-band components
- Commissioning and running of XBoxes

Funding required

- One PDRA for 2 years (£180k+£20k Swiss top up) matched with another PDRA based at Lancaster.
- £10k to bond final crab cavity structure
- Travel (£20k)
- Top-up to make 3 x CERN studentships, one for each topic, (from Walter) fully funded for 2 years, remaining years will be paid by Lancaster (£85k)
- Lancaster will provide academic effort

- Total=£315k

Thank you!