The Cockcroft Institute
of Accelerator Science and Technology

LANCASTER UNIVERSITY

LLRF for EUCARD
Crab Cavities

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Paris

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EuCARD

ASTeC

Crab Parameters

Simpler design required

Huge beam loading and wakes

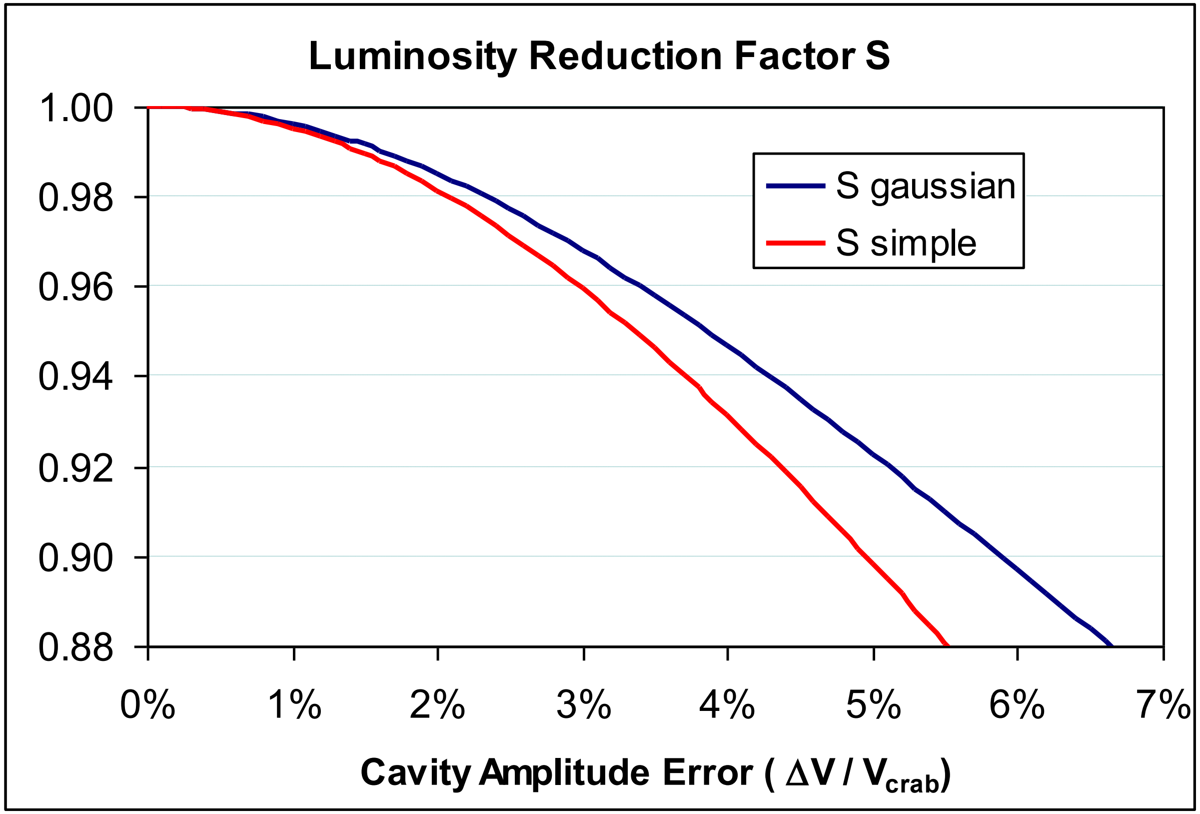
	Beam Energy	Bunch Charge	Bunch Repitition	Crab peak Power	Bunch Length
ILC	0.5 TeV	3.2 nC	3 MHz	1.24 kW	300 μm
CLIC	1.5 TeV	0.6 nC	2 GHz	288 kW	100 μm
LHC	7 TeV	18.4 nC	40 MHz	12.7 kW	7.55 cm

Stiff beam, needs a large voltage and/or small crossing angle

Short timescales, high current

Long bunch = low frequency to avoid non-linear kick

Tolerance for Gaussian Amplitude Errors



s_z = 44000 nm
s_x = 45 nm
q_c = 0.02 rad

$$\bar{S}\left(\frac{\Delta V}{V_{crab}}\right) = \frac{1}{2\pi\left(\frac{\Delta V}{V_{crab}}\right)^2}\int_{-\infty}^{\infty}\frac{dV_1}{V_{crab}}\int_{-\infty}^{\infty}\frac{dV_2}{V_{crab}}\frac{\exp\left\{-\frac{(V_1/V_{crab})^2}{2(\Delta V/V_{crab})^2}\right\}\exp\left\{-\frac{(V_2/V_{crab})^2}{2(\Delta V/V_{crab})^2}\right\}}{\sqrt{1+\left\{\frac{\sigma_z\theta_c}{4\sigma_x}\frac{\left(|V_1|+|V_2|\right)}{V_{crab}}\right\}^2}}$$

Kick and tolerance for 3 TeV CM

To minimise required cavity kick R12 needs to be large (25 metres suggested)
Vertical kicks from unwanted cavity modes are bad one needs R34 to be small.
For 20 mrad crossing and using as 12 GHz structure

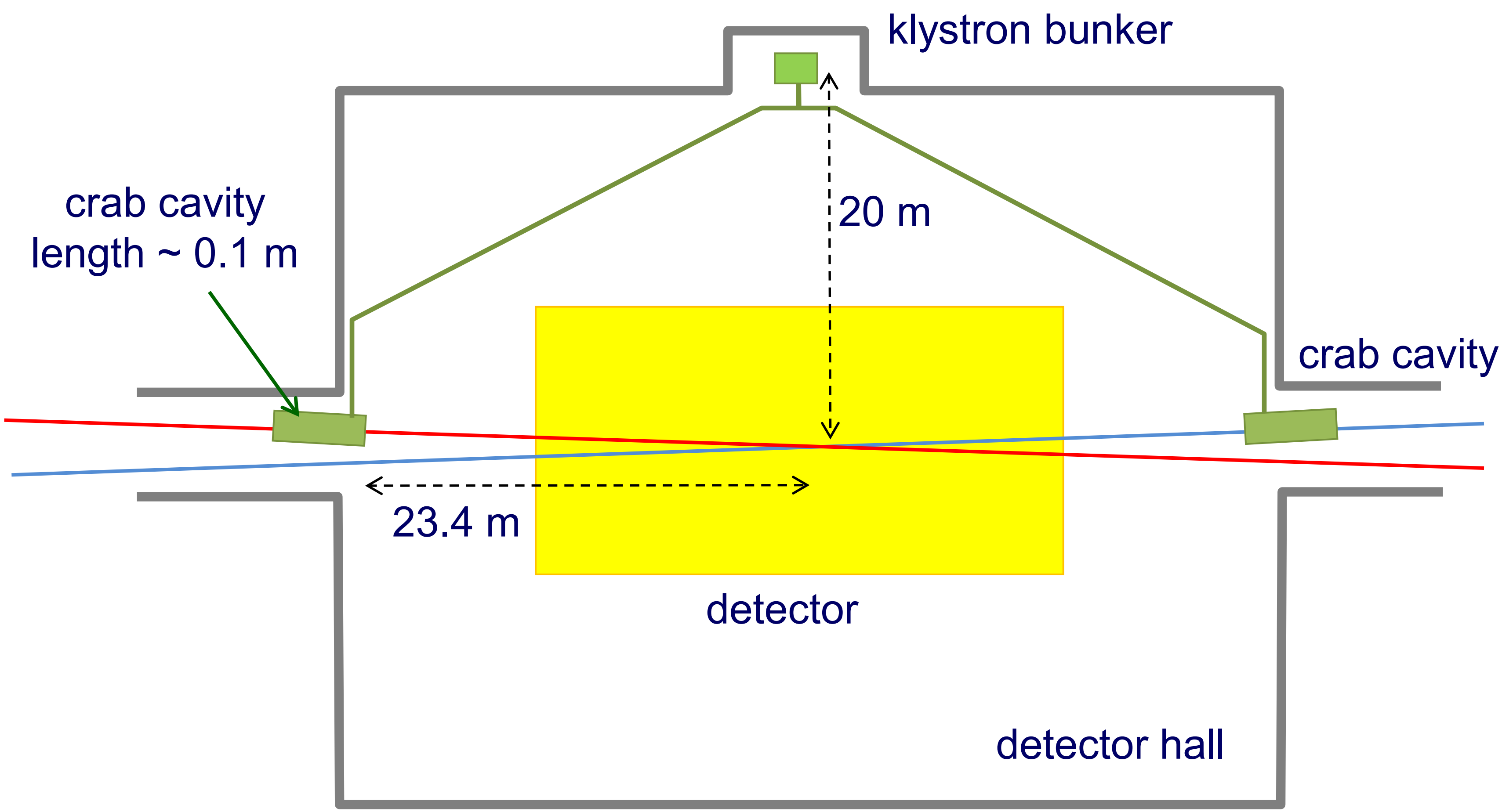
$$V_{crab} = \frac{\theta_c E_o c}{2R_{12}\omega} = \frac{2\times10^{-2}\times1.5\times10^{12}\times3\times10^{8}}{2\times25\times2\pi\times12\times10^{12}} = 2.4\,\mathrm{MV}$$

Error in kick tilts effective collision from head on.

Luminosity Reduction Factor $$S \approx \frac{1}{\sqrt{1+\left\{\frac{\sigma_z\theta_c}{4\sigma_x}\frac{\left(|\delta V_1|+|\delta V_2|\right)}{V_{crab}}\right\}^2}}$$ gives

amplitude error on each cavity	**1.0%**	**1.5%**	**2.0%**	**2.5%**	**3.0%**
luminosity reduction	**0.9953**	**0.9914**	**0.9814**	**0.9714**	**0.9596**

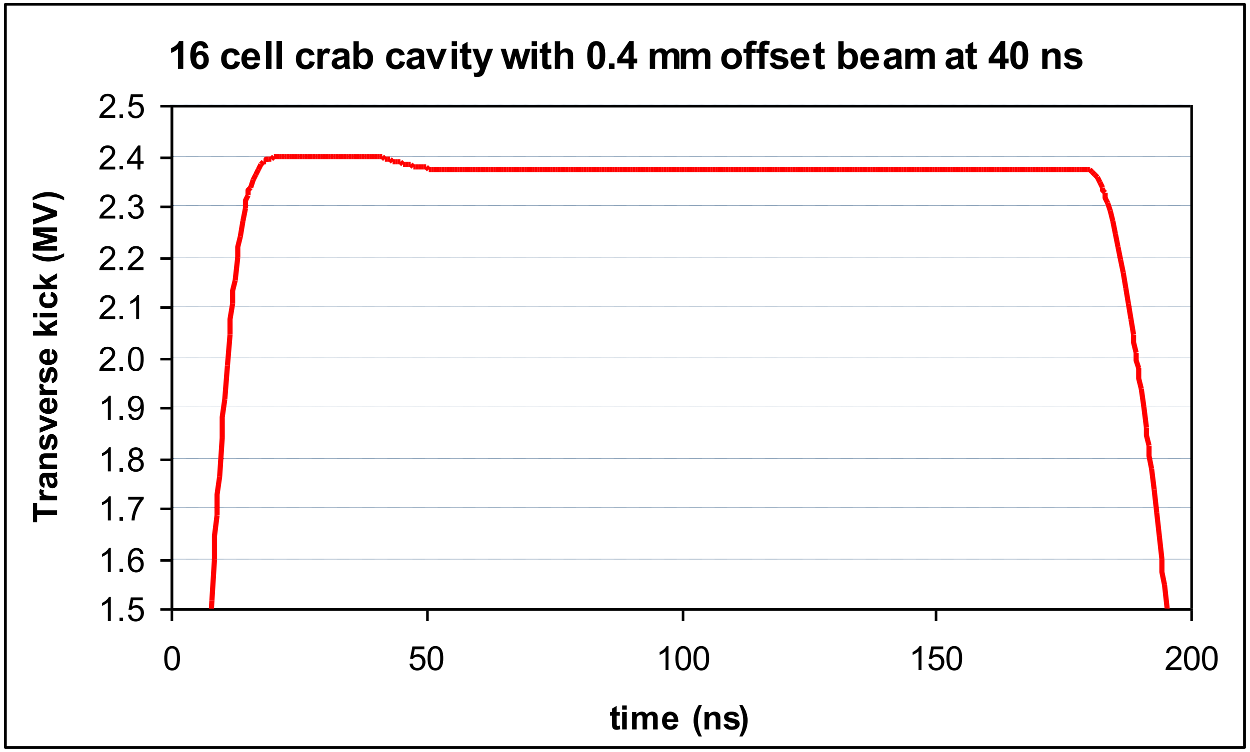
Waveguide routing?



CLIC Solution

Wakefields	**Large irises** **Small number of cells** **Strong damping**
Phase and amplitude control	**Passive during 156 ns bunch train**
Beamloading compensation	**High energy flow through cavity** * ***small number of cells*** * ***high group velocity*** * ***low efficiency***
Phase synchronisation (4.4 fs)	**Same klystron drives both cavities** **Temperature stabilized waveguide**
Phase reference	**Optical interferometer**
Phase measurement calibration	**DBM and** **Down conversion to ~ 1 GHz,** **Digital phase detection** **Staggered sample and hold**
Phase stability	**Thick irises** **Strong cavity cooling**

Fill Time and Beamloading



Input = 6.45 MW
Initial kick = 2.40 MV
Plateau = 2.37 MV

v_g = group velocity
L_{cell} = cell length
U_n = energy in cell n
f_{rep} = bunch frequency
q = bunch charge
dx = bunch offset

For each cell solve energy equation

$$\frac{dU_n}{dt} = \frac{(U_{n-1} - U_n)}{L_{cell}} v_g \quad - \quad U_n \frac{\omega}{Q} \quad - \quad q f_{rep} \delta x \, \omega \sqrt{\frac{\omega}{c} \frac{R}{Q} U_n} \qquad (n > 1)$$

convection - dissipation - beamloading

Beamloading in 16 Cell Cavity

Cavity Parameters as on last slide and Q = 6381

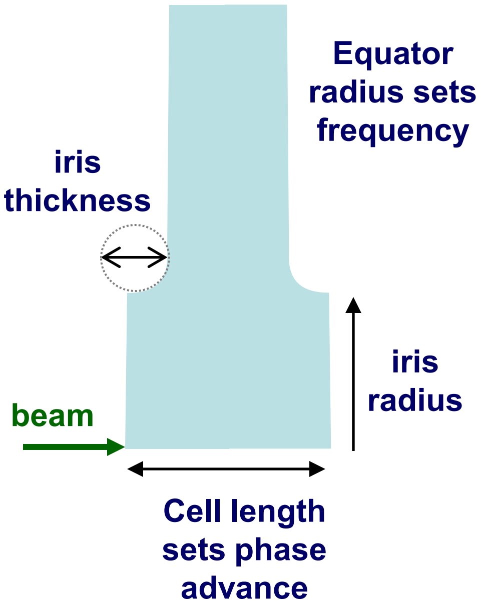
Beam offset (mm)	-0.4	0.0	0.4
Power entering cell 1 (MW)	6.388	6.388	6.388
Power leaving cell 16 (MW)	5.619	5.341	5.063
Ohmic power loss (MW)	1.071	1.047	1.023
Beamload power loss (MW)	-0.302	0.000	0.302
E max for cell 1 (MV/m)	51.1	51.1	51.1
Efficiency	12.04%	16.39%	20.74%
Kick (MV)	2.428	2.400	2.372

A short inefficient cavity with a high power flow achieves adequate amplitude stability

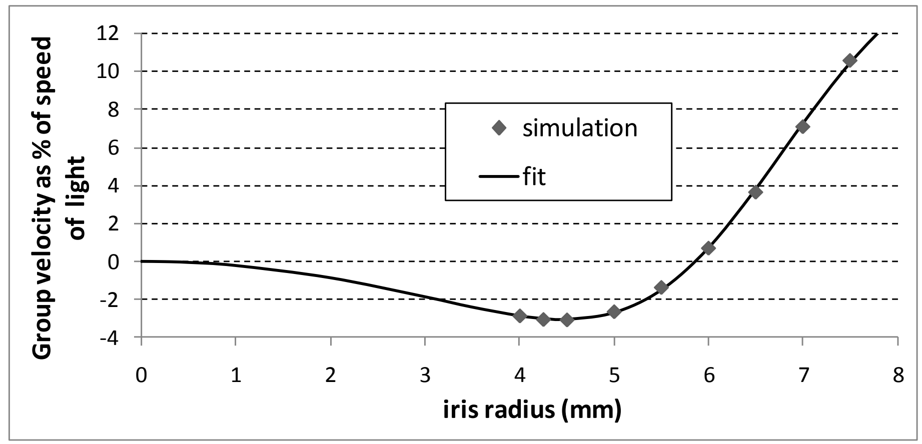
Can we make the gradient?

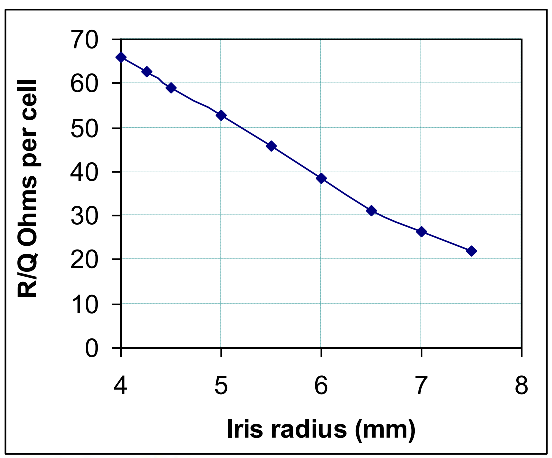
Is pulse heating OK (consider low temperature operation)?

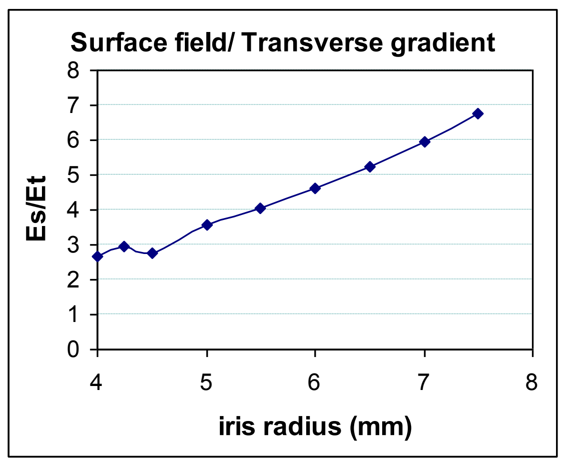
Cavity variables

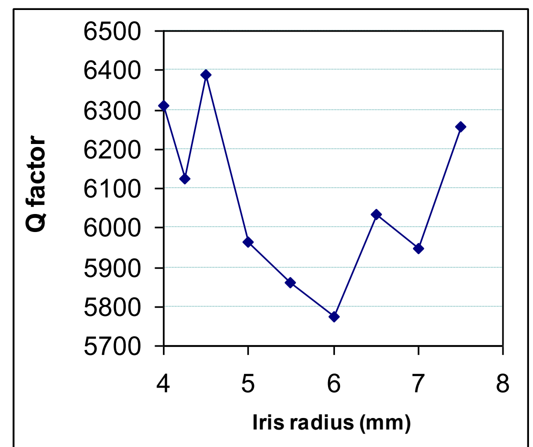


Given the maximum surface fields and the available power one must chose number of cells and iris parameters to maximise luminosity

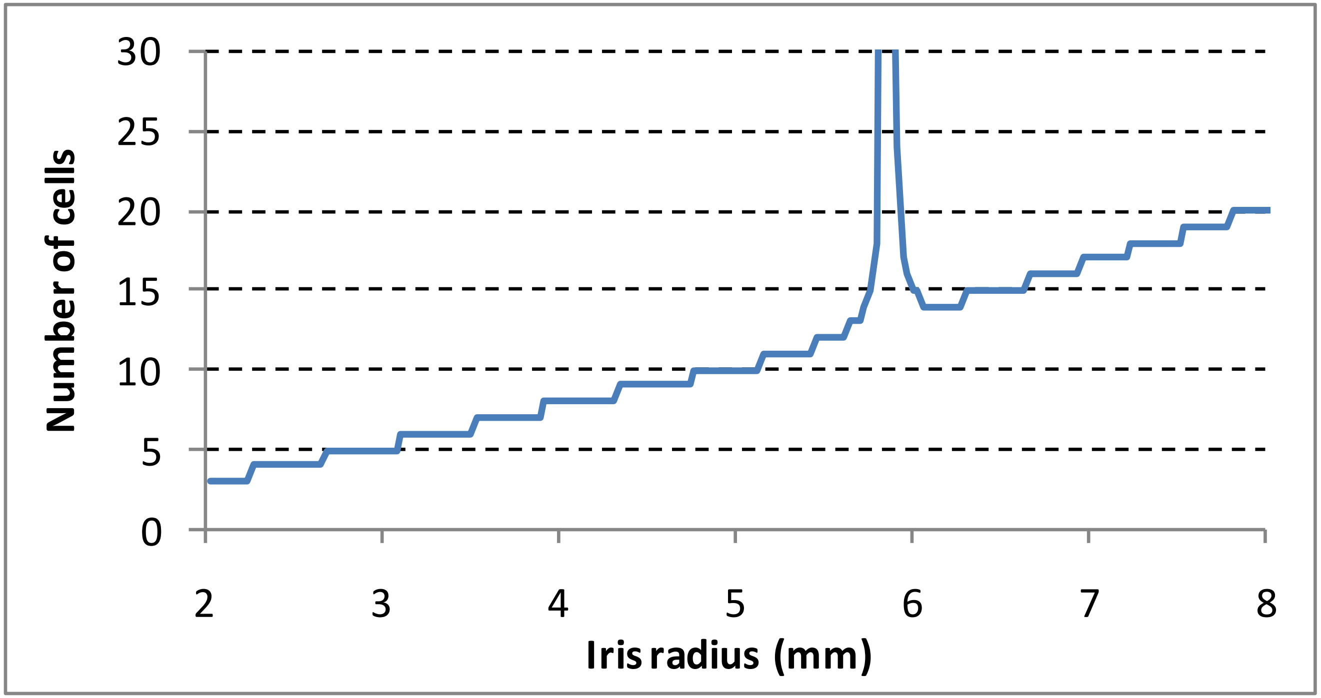






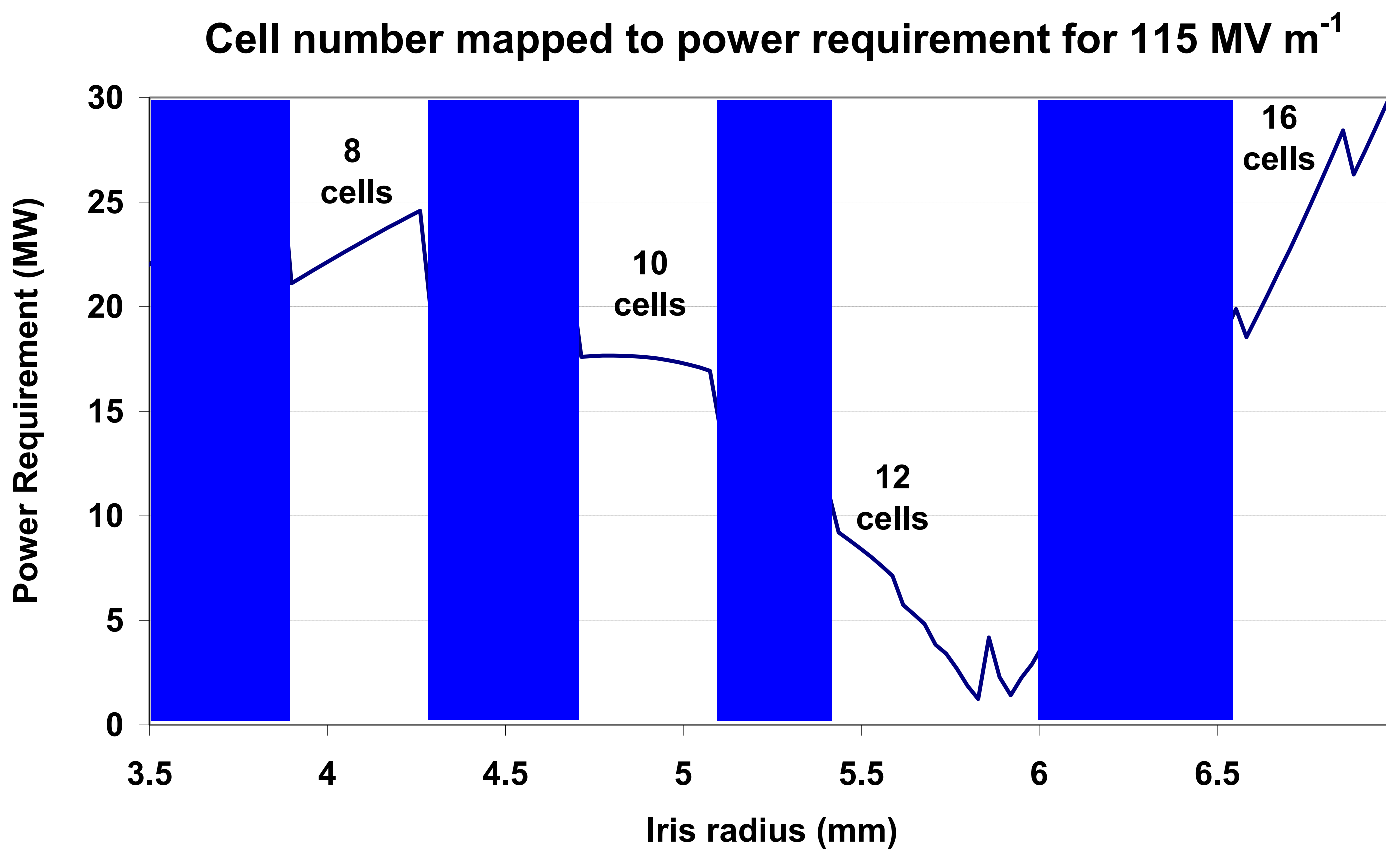


Cell number for fixed surface field



Number of cells for 2.4 MV transverse kick not exceeding surface field 110 MV m^{-1}.

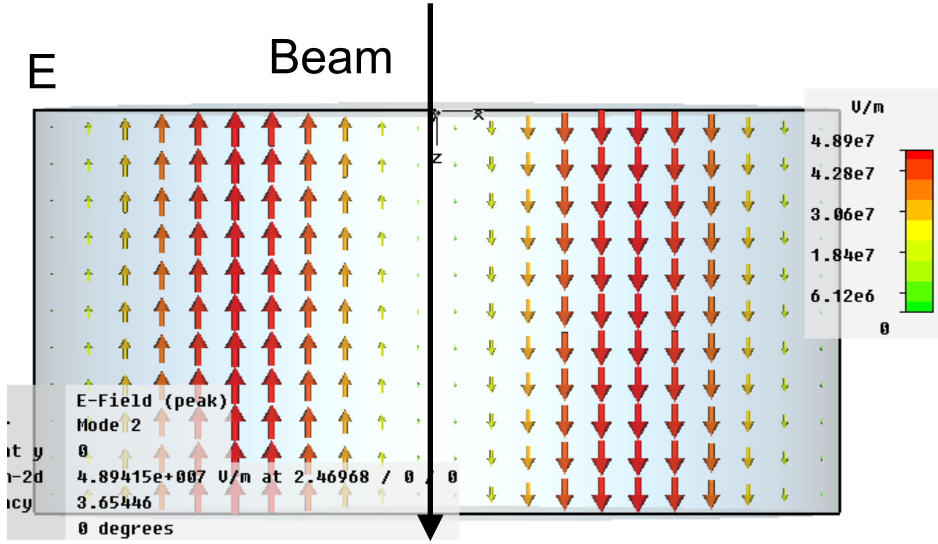
Cell Number Optimisation



Cavity power requirement for a beam offset of 0.375 mm

Beam Loading

- As the electric field in dipole cavities vary with offset the beam-loading changes with time and cannot be predicted.
- The beam is too short for feedback.
- Need to design to minimise the effect (increase convection or dissipation)



For each cell solve energy equation

$$\frac{dU_n}{dt} = \frac{(U_{n-1} - U_n)}{L_{cell}} v_g \; - \; U_n \frac{\omega}{Q} \; - \; q f_{rep} \, \delta x \, \omega \sqrt{\frac{\omega}{c} \frac{R}{Q} U_n} \qquad (n > 1)$$

convection - dissipation - beamloading

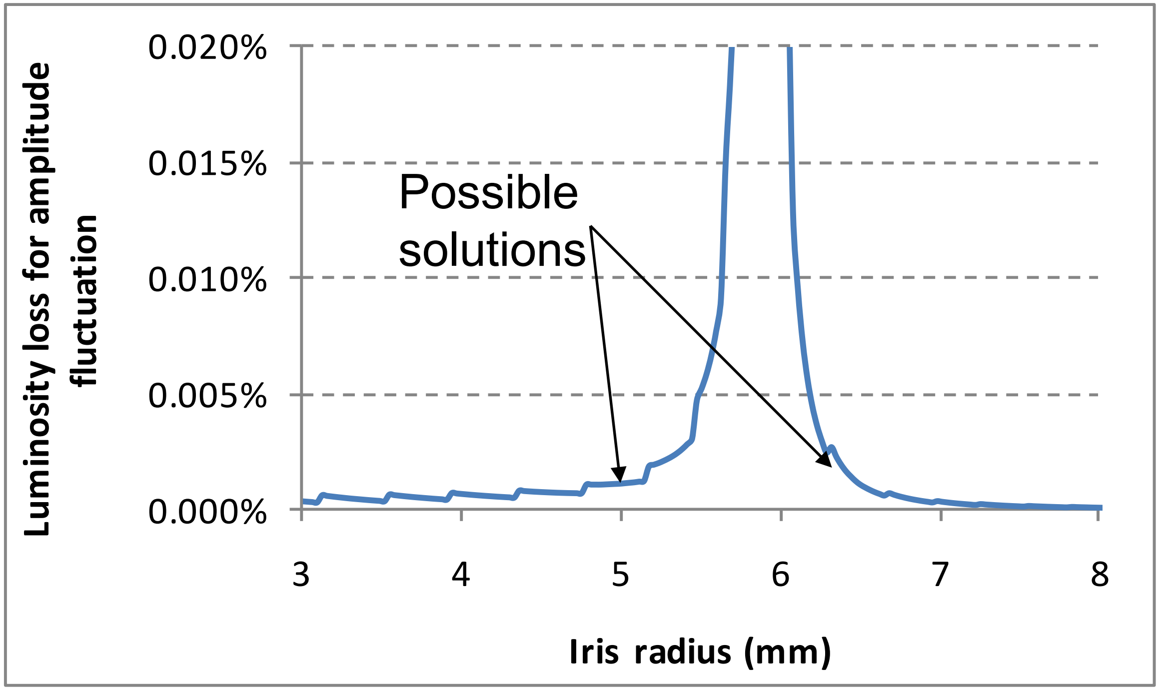
Luminosity loss

Increasing dissipation increases heating, this is not recommended

We can increase power convection by increasing the structure group velocity.

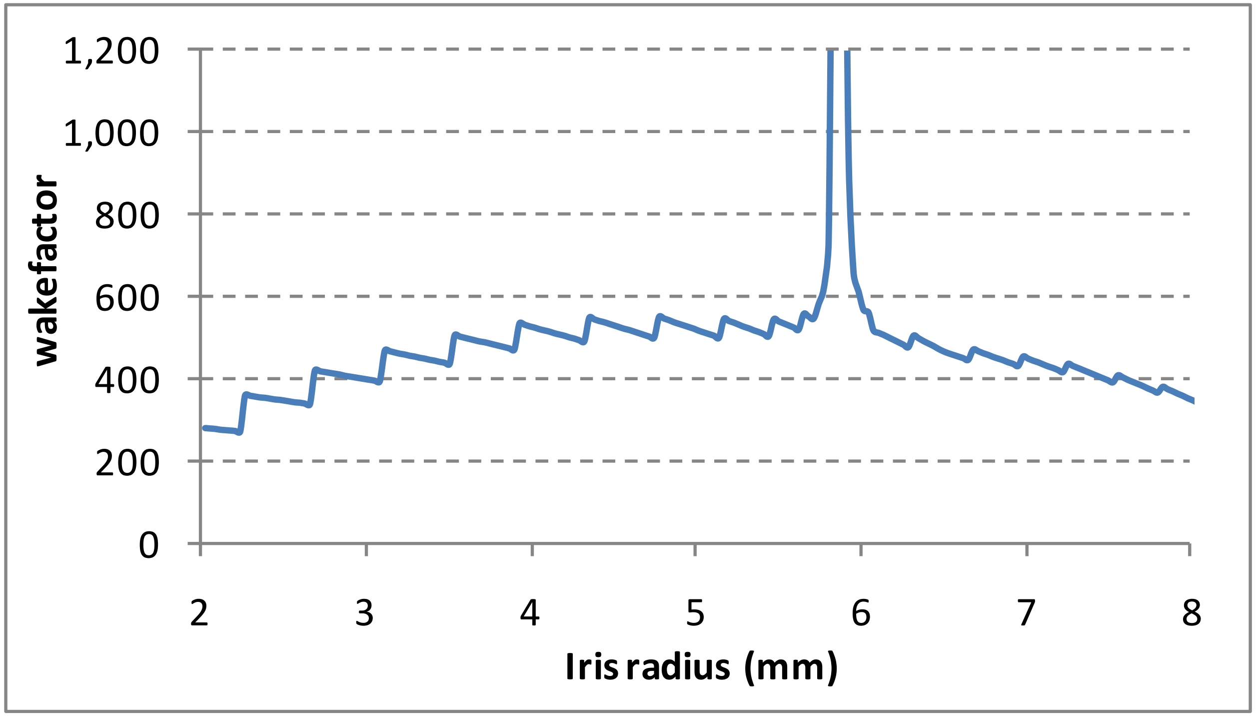
The group velocity is dependant on the iris radius.

However we have limited power (20 MW) so we can only increase the convection so much.



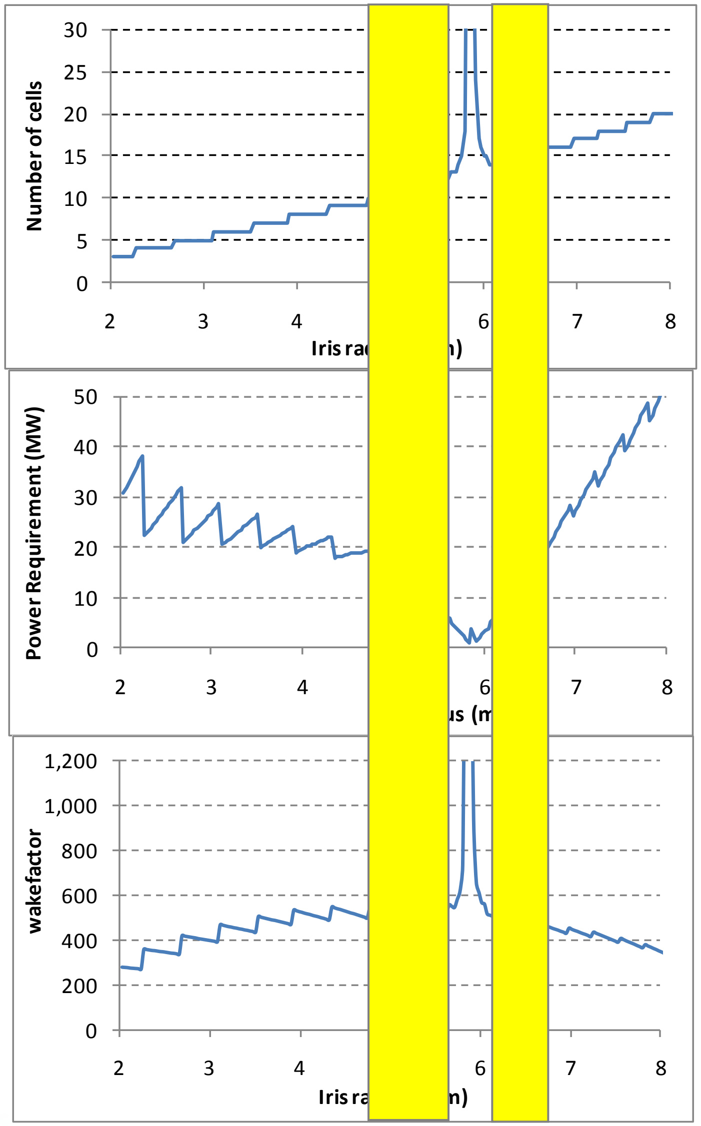
Luminosity loss for a beam offset of 0.125 mm

Wakefactor ~ R/Q times cells

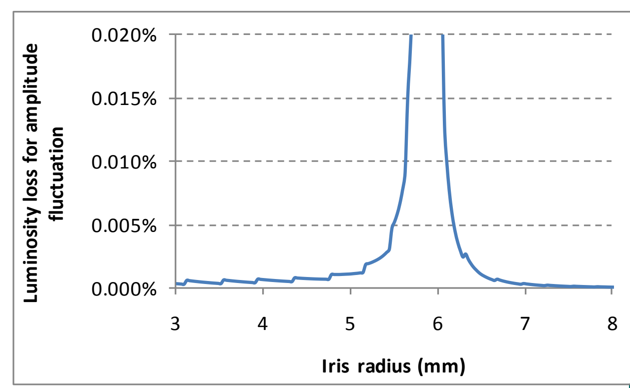


R/Q multiplied by cell number plotted against iris radius to give figure of merit for wakefields

Choice



Initial studies have started with the 10 cell option



Waveguide choice

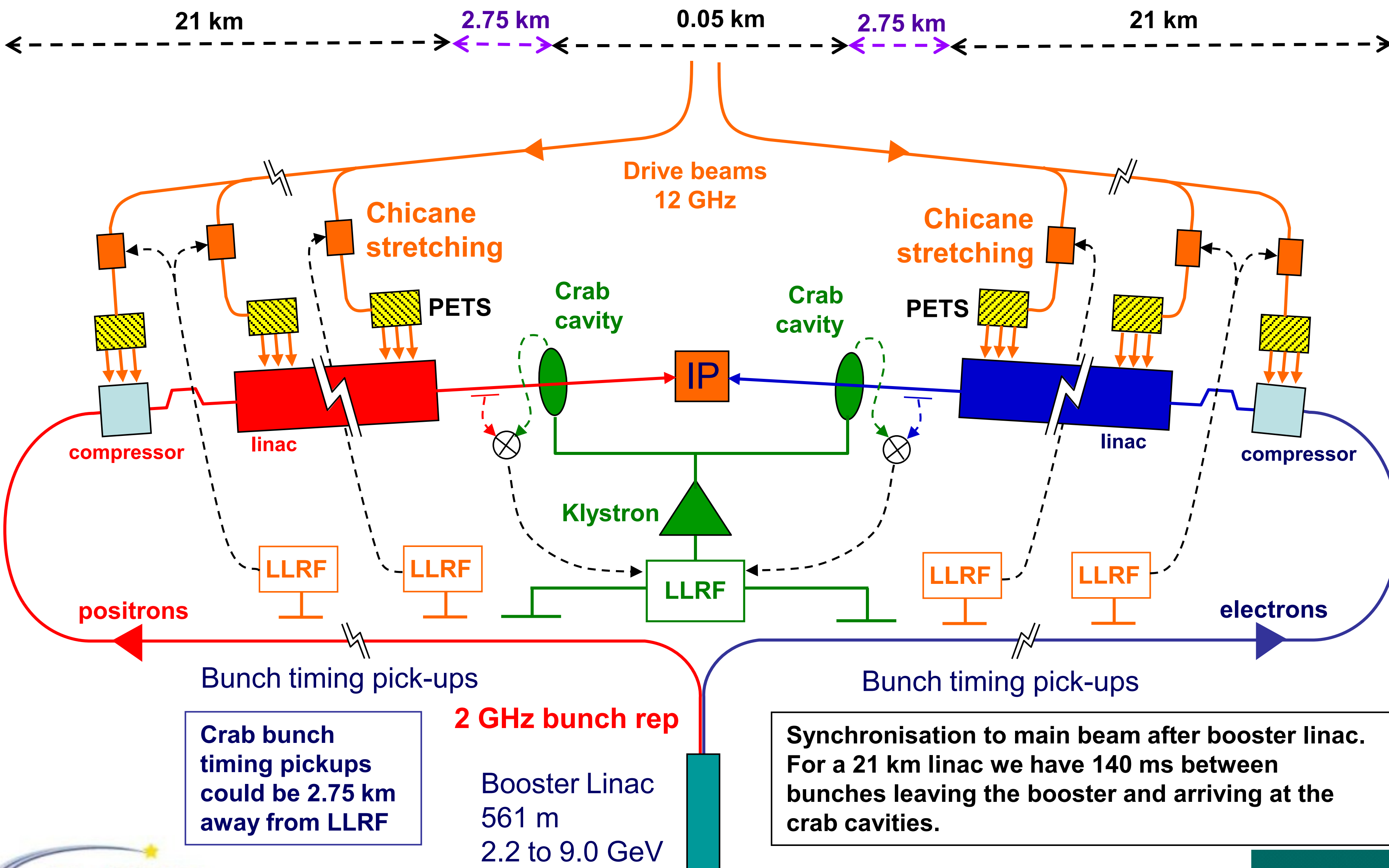
Assume 40 m waveguide run from Klystron to each Crab cavity

For copper s =5.8e7 S/m and at 11.994 GHz	Attenuation	Transmission	Over moded
Rectangular TE10 EIA90 (22.9 x 10.2 mm)	0.098 dB/m	40.6%	no
Rectangular TE10 special (24 x 14 mm)	0.073 dB/m	51.3%	no
Circular TE11 (r = 9.3 mm)	0.119 dB/m	33.3%	no
Circular TE11 (r = 12 mm)	0.055 dB/m	60.4%	TM10
Circular TE01 (r = 40 mm)	0.010 dB/m	91.2%	extremely

Available klystron has nominal output of 50 MW
Divide output for two beam lines = 25 MW
For standard rectangular waveguide we have 10.2 MW available **(OK for 15 cells)**
For special rectangular waveguide we have 12.8 MW available **(OK for 11 cells)**
For circular 12mm TE11 waveguide we have 15.1 MW available **(OK for 11 cells)**

(note that mode conversion from circular TE11 to circular TM10 is vanishingly small for properly designed bends)

CLIC LLRF Timing

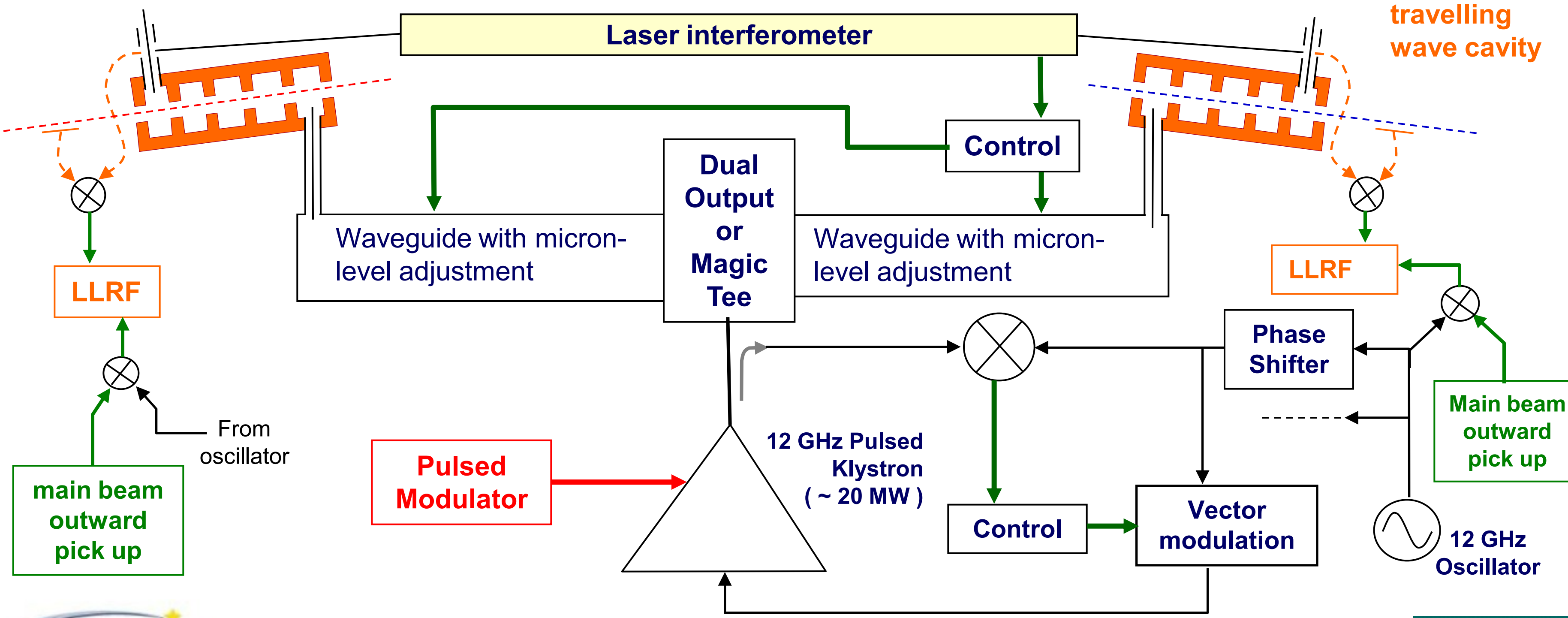


Crab Cavity RF

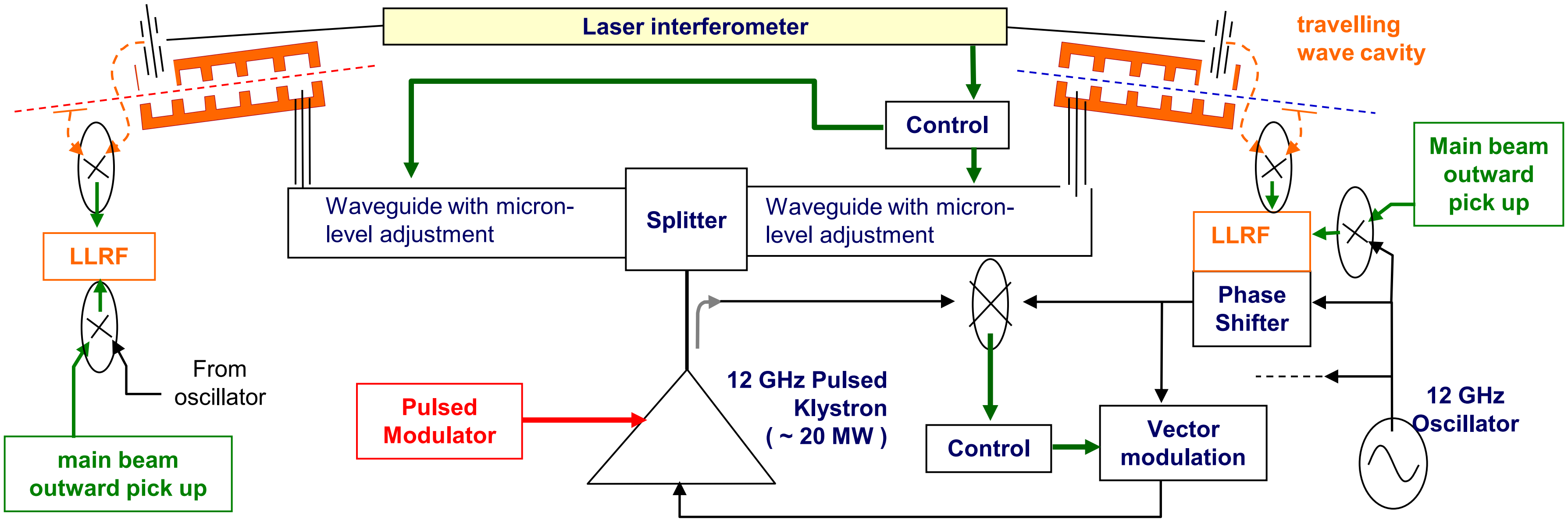
- Beamloading constrains us to high power pulsed operation
- Intra bunch phase control looks impossible for a 140 ns bunch

SOLUTION

- One Klystron (~ 20 MW pulsed) with output phase and amplitude control
- Intra bunch delay line adjustment for phase control (i.e. between bunch trains)
- Very stable cavities



RF Layout and Procedure

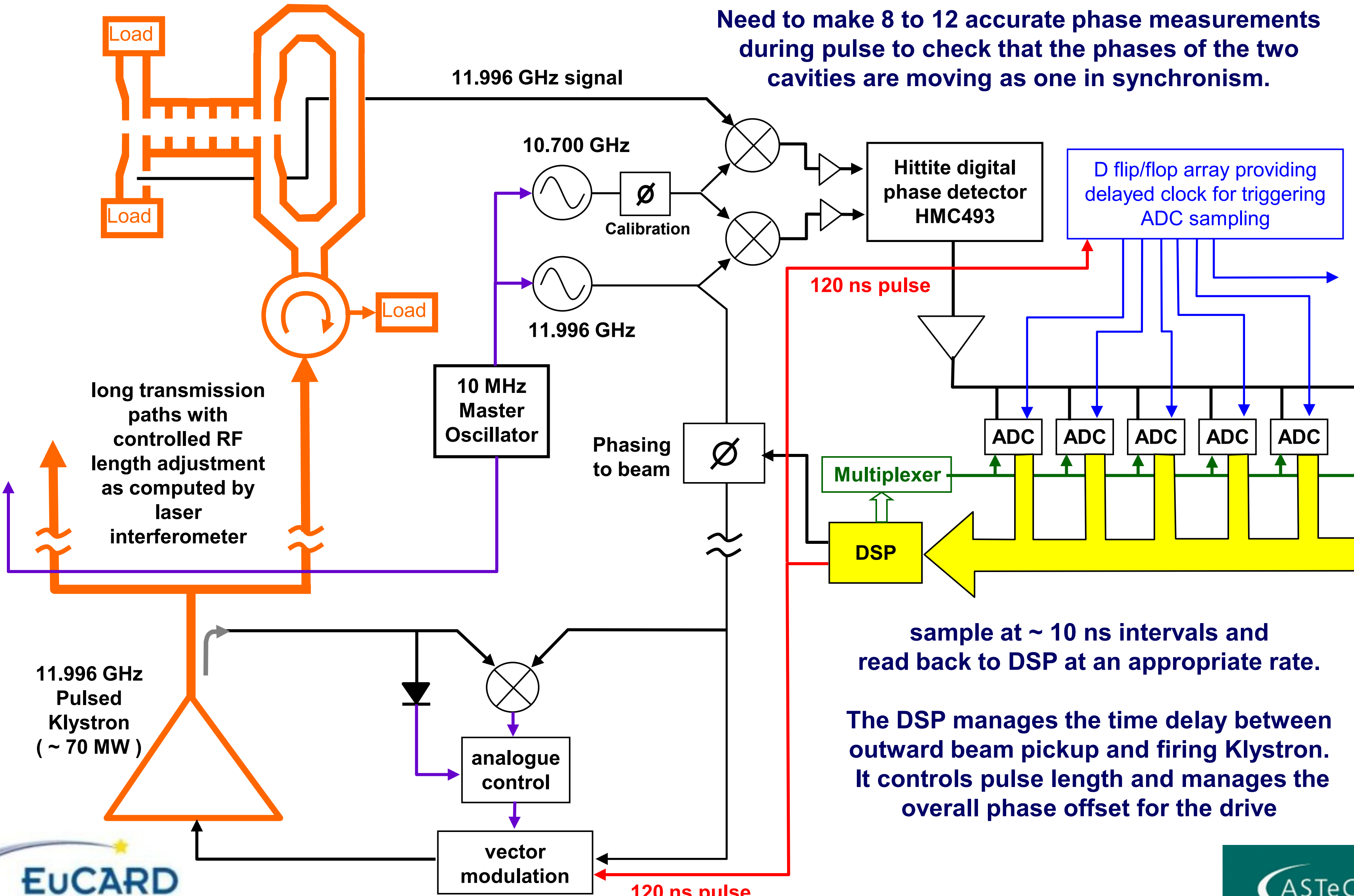


Once the main beam arrives at the crab cavity there is insufficient time to correct beam to cavity errors. These errors are recorded and used as a correction for the next pulse.

0. Send pre-pulse to cavities and use interferometer to measure difference in RF path length (option1)
1. Perform waveguide length adjustment at micron scale (option 2 use measurements from last pulse)
2. Measure phase difference between oscillator and outward going main beam
3. Adjust phase shifter in anticipation of round trip time and add offset for main beam departure time
4. Klystron output is controlled for constant amplitude and phase
5. Record phase difference between returning main beam and cavity
6. Alter correction table for next pulse

Phase measurement

Need to make 8 to 12 accurate phase measurements during pulse to check that the phases of the two cavities are moving as one in synchronism.



sample at ~ 10 ns intervals and read back to DSP at an appropriate rate.

The DSP manages the time delay between outward beam pickup and firing Klystron. It controls pulse length and manages the overall phase offset for the drive

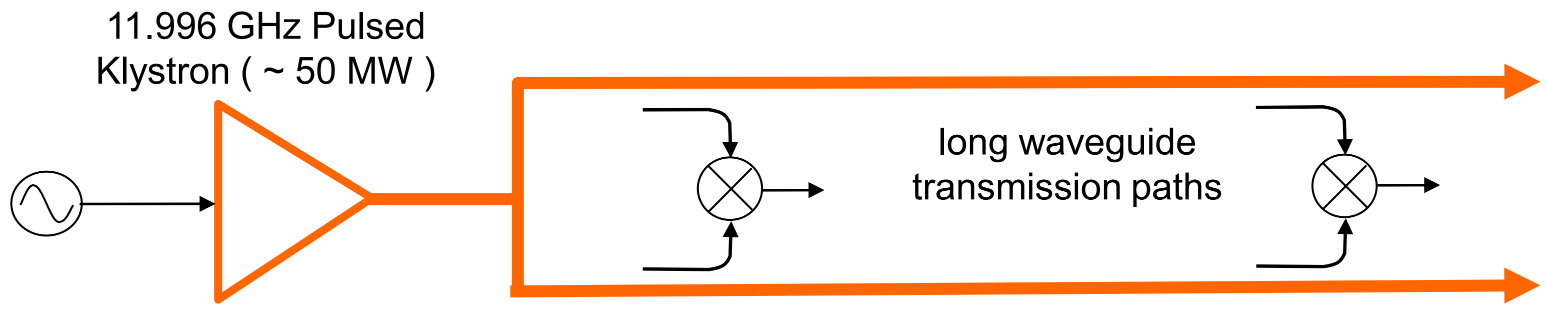
Distribution Stability Requirement

- r.m.s. cavity to cavity synchronisation requirement is 4.4 fs
- hence r.m.s klystron to cavity stability requirement is 3.1 fs (two paths)
- phase velocity of light in the waveguide will be just over 3.0×10^8
- hence waveguide length must be steady at the precision of 10^{-6} metres

(Expansion example without expansion joints)
Control waveguide temperature to say 0.3^oC.
Copper expansivity 17×10^{-6} K^{-1}.
40 metre waveguide could vary in length by 200 μm.
Waveguide wavelength ~ 25 mm
Expansion ~ 200 μm
Phase shift ~ 2.9 degrees which is 150 times the allowance!

It is probably that the waveguide will have expansion joints and so the real question is about the lateral stability of the cavity and the klystron.

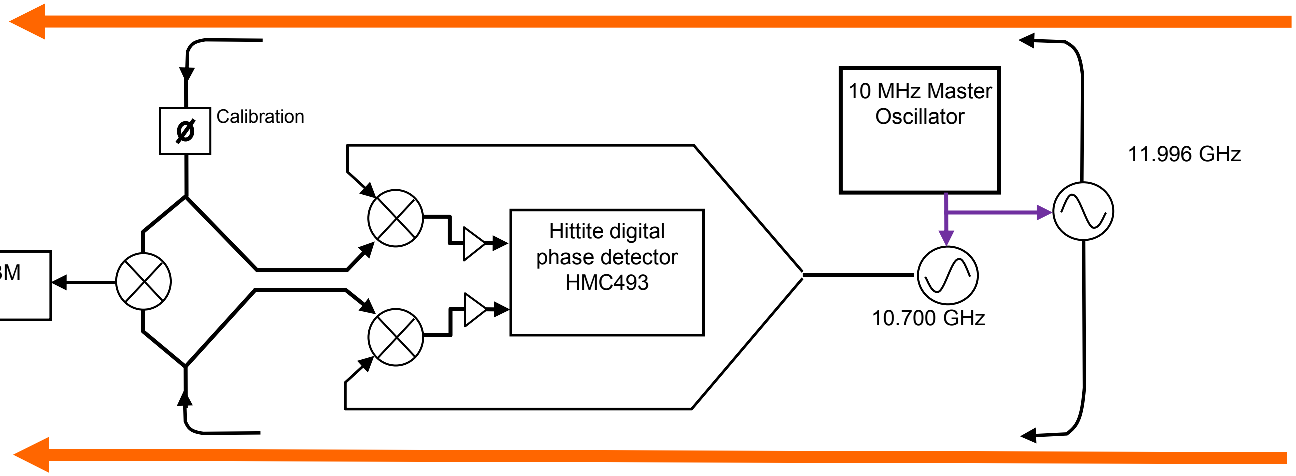
Distribution Experiment



Double balanced mixer Mini-circuits SIM-24MH+
RF 7.3 GHz to 20 GHz, IF DC to 7.2 GHz
Need about 24 dB of amplification to resolve 1 milli-degree at 12 GHz, signal to noise before amplifier for 40 MHz bandwidth ~ 6 dB
Measurement looks feasible.

But need digital phase detection as before for calibration

Board Development



The calibration of the DBM is performed using a digital phase detector after down-conversion to 1.3 MHz.

This hardware is underdevelopment but is so far not meeting the resolution specification.