Microwave accelerating structures: an innovative parallel coupled electron LINAC

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GIOVANNI CASTORINA

UNIVERSITÀ degli STUDI di CATANIA

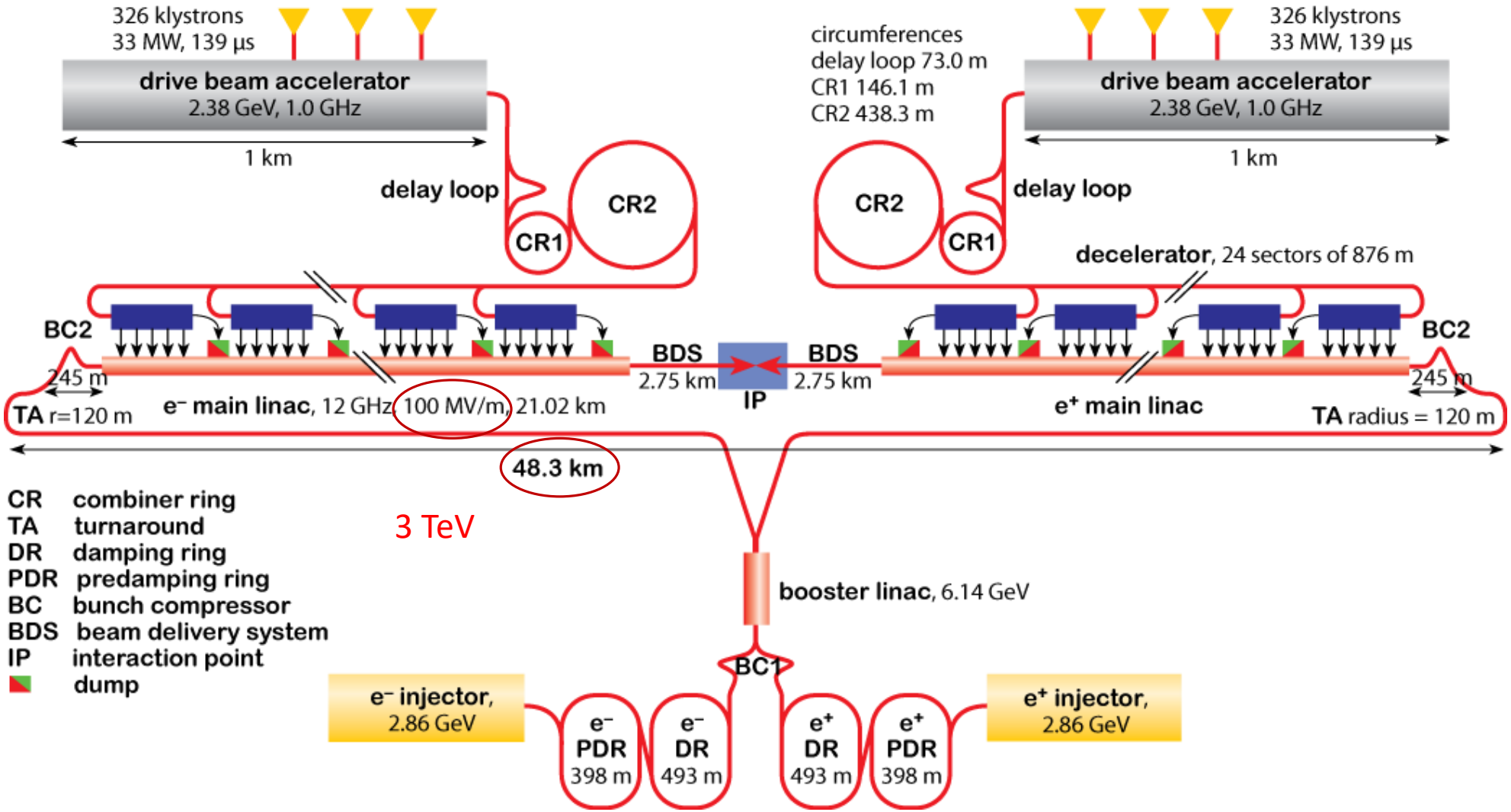
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

siem SOCIETÀ ITALIANA DI ELETTROMAGNETISMO

Outline

- Movitation for high gradient accelerating structures
- Scaled Kilpatrick Criterion and Scaled Power, Pulse Heating and Modified Poynting Vector
- Parallel Coupled Accelerating Structure (PCAS) for high gradient operation with very short pulse length
- Beam Dynamics of PCAS

Why high gradient LINAC?



New Quantities for Design of High Gradient Accelerating Structures

Historically only the Kilpatrick Criterion has been employed as a guideline to design an accelerating structures. Today it is possible to determine other quantities to estimate the breakdown performance of an accelerating section.

- *Scaled Kilpatrick Criterion*
- *Scaled Power*
- *Surface Electric Field*
- *Pulse Heating*
- *Modified Poynting Vector*

Scaled Kilpatrick Criterion and Scaled Power

The Kilpatrick criterion for short pulse (<1 μs) with respect to the filling time of the section provides a scaling law [1] for the maximum electric field E_s obtainable and it is proportional to:

$$E_s \text{ α } f^{\frac{1}{2}}/t^{\frac{1}{4}}$$

where *f* is the operation frequency and *t* is the pulse length.

For travelling wave section another quantity can be used to calculate the breakdown performance, the scaled power. It is defined as:

$$P_s = \frac{Pt^{\alpha}}{C}$$

where P is the power, t the pulse length, α is a material dependent exponent (1/3 for copper); C the iris circumference and it not should exceed the value of 18 MW/mm*ns^α.

[1] Wangler, Thomas P. *RF Linear accelerators*. John Wiley & Sons, 2008.
[2] Wuensch, W. *Progress in understanding the high-gradient limitations of accelerating structures*. No. CERN-OPEN-2007-008. 2007.

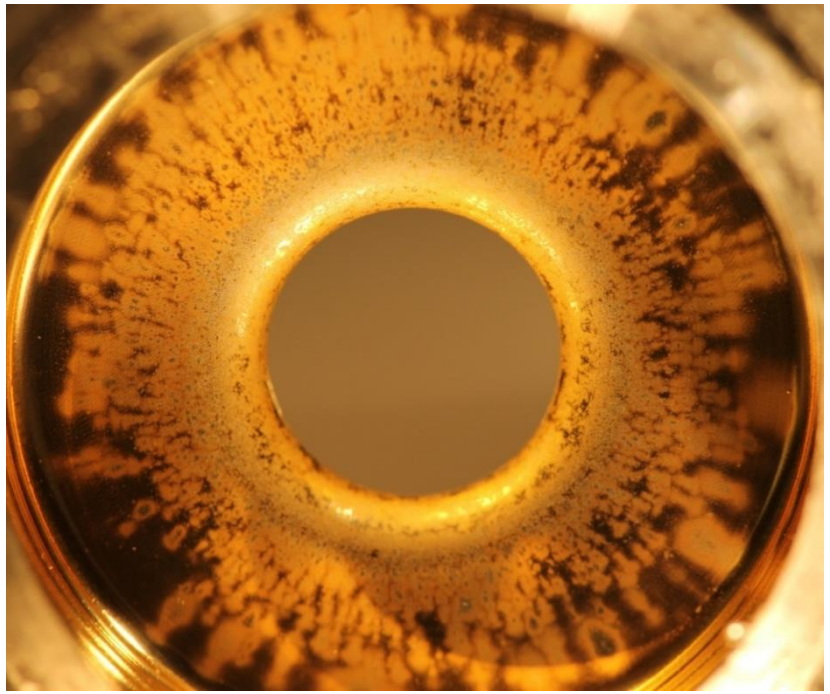
Surface Electric Field and Pulse Heating

Constraints to local electric and magnetic fields have been investigated in [1] and [2]. These studies show an upper limit on electric and magnetic surface peak fields for safely operation. Maximum surface electric field do not exceed the 285 MV/m.

The surface magnetic field is responsible for local thermal heating and it can be roughly evaluated through underlying model

$$\Delta T = \frac{|H|_{\parallel}^{2}\sqrt{t}}{\sigma\delta\sqrt{\pi\rho c_{\varepsilon} k}}$$

where H is the magnetic field, t the pulse length, σ the conductivity of the material, δ the skin depth, ρ the density, c_{ε} is the specific heat and k the thermal conductivity of the metal. For a fixed material, frequency and pulse length this fix an upper limit on the magnetic field.



Iris damage due to breakdown.

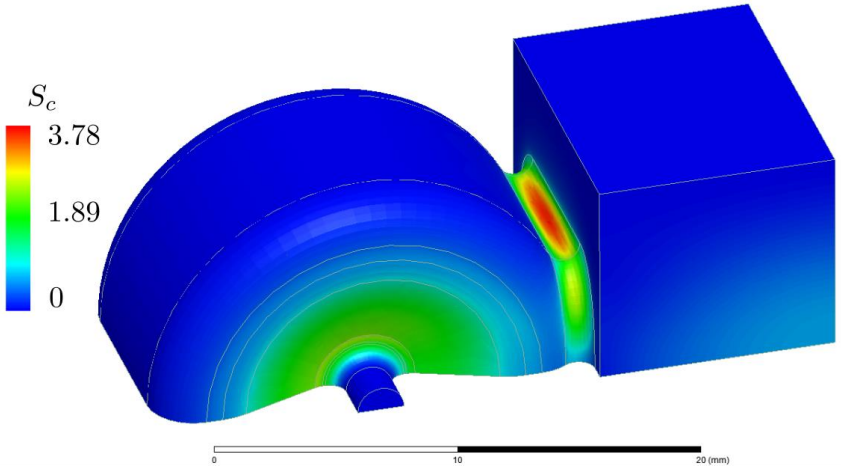
[1] Wang, J. W., et al. "SLAC/CERN high gradient tests of an X-band accelerating section." *Particle Accelerator Conference, 1995., Proceedings of the 1995*. Vol. 1. IEEE, 1995.
[2] Dolgashev, Valery A., and Sami G. Tantawi. "Effect of RF Parameters on Breakdown Limits in High-Vacuum X-Band Structures." *AIP Conference Proceedings*. Eds. Steven H. Gold, and Gregory S. Nusinovich. Vol. 691. No. 1. AIP, 2003.

Modified Poynting Vector

The modified Poynting vector is a local quantity defined as:

$$\boldsymbol{S_c} = Re\{\boldsymbol{S}\} + \frac{1}{6} Im\{\boldsymbol{S}\}$$

The modified Poynting vector combines the surface electric field with the scaled power limits and it can be employed as a RF breakdown constraint. Its numerical value should not exceed 5 MW/mm^2 in order to have BDR below 10^{-6} bpp/m at pulse length of 200 ns [1]. Pulse heating and modified Poynting Vector are often sufficient as high gradient constraints for accelerating structures design. By being independent frequency figures of merit, they are efficient for high frequency design.

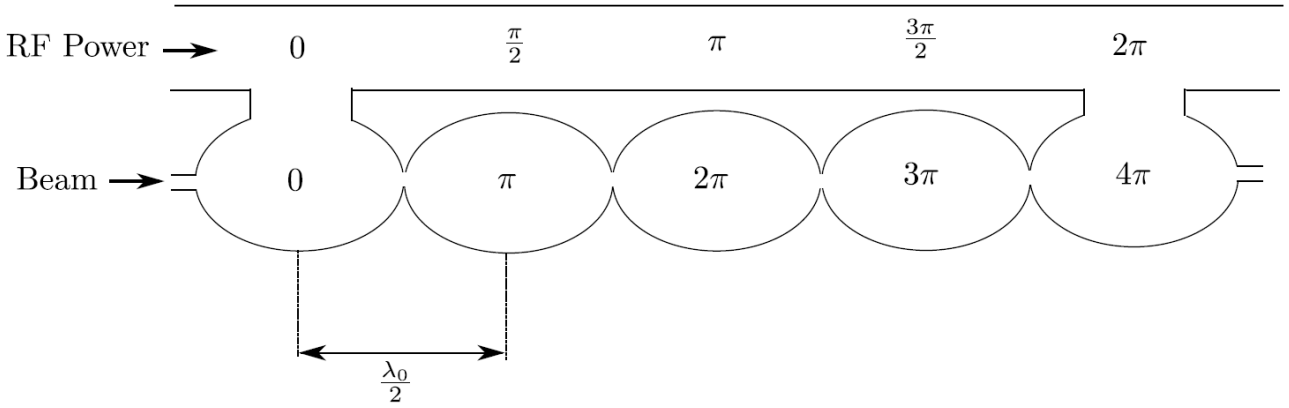


Modified Poynting vector in a single hole coupled cell

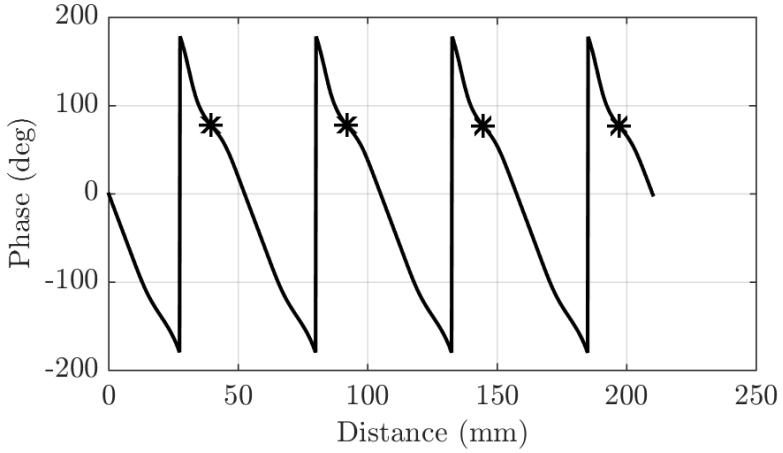
[1] Grudiev, Alexej, S. Calatroni, and W. Wuensch. "New local field quantity describing the high gradient limit of accelerating structures." *Physical Review Special Topics-Accelerators and Beams* 12.10 (2009): 102001.

New structures for high gradient acceleration

At LNF-INFN a parallel coupled accelerating structure (PCAS) has been design and simulated. This kind of section can overcome some issue of the common TW section. RF power is coupled every fourth cell from a parallel waveguide with a large coupling hole in order to obtain an high β coefficient coupling.
However due to the higher phase velocity in the waveguide, respect to speed of light, the phase matching scheme is not trivial. The phase velocity in waveguide can be tuned by varying the dimension of the waveguide or by tuning the distance between two consecutive coupled cells.



Phase matching scheme for a π-mode cell with coupling every 4 cells.

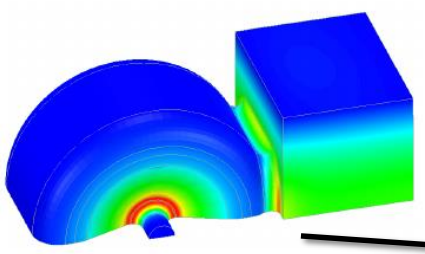


Phase plot along the section

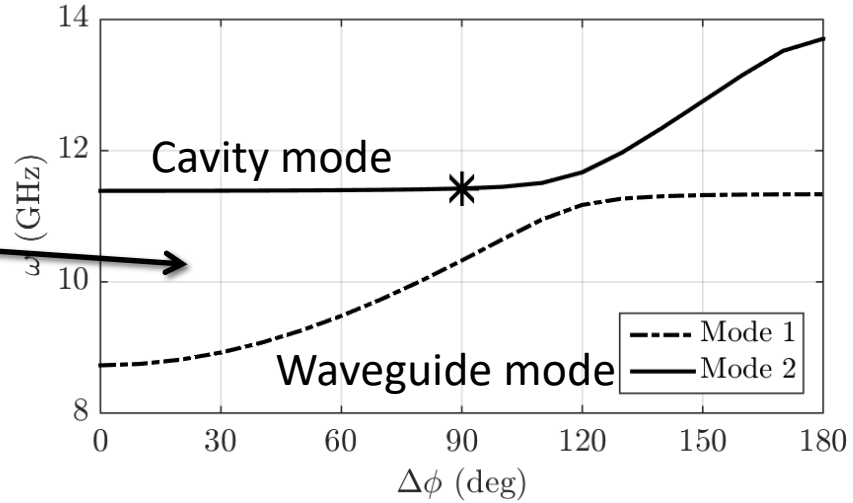
Group velocity and filling time

The PCAS is a bi-modal device:

1. Propagating mode in waveguide
2. Standing mode in cavity

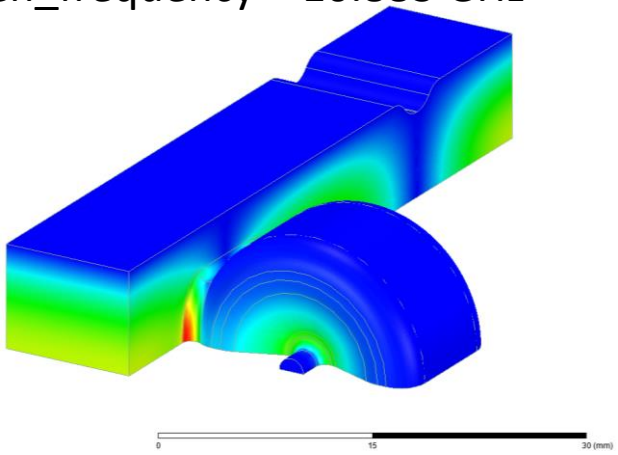


0.43*c < Group velocity < 0.82*c

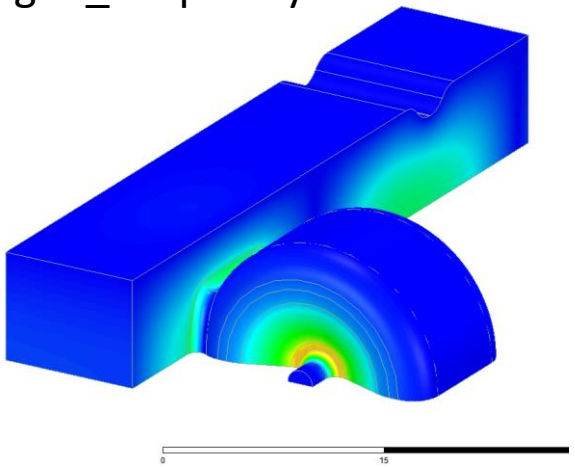


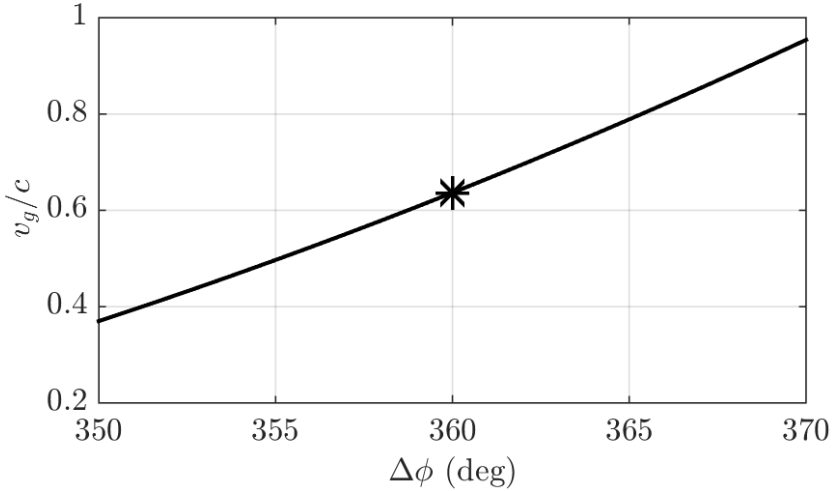
The group velocity can be calculated from the dispersion Diagram of a full period structure

Eigen_frequency = 10.883 GHz

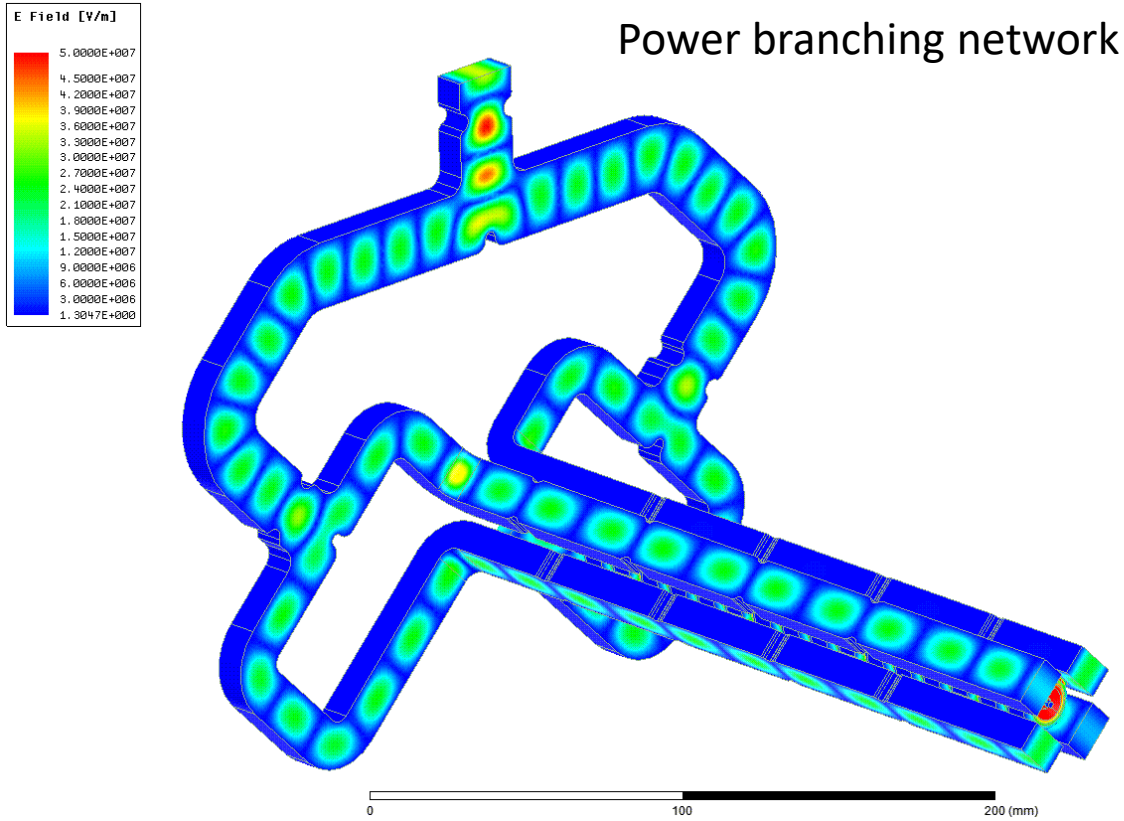


Eigen_frequency = 11.423 GHz

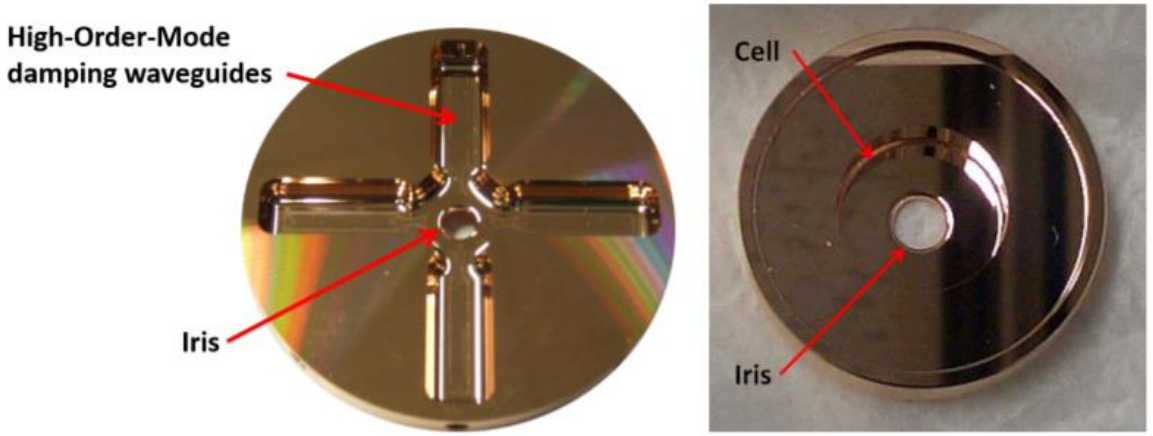




Frequency and time domain simulation of PCAS



Power branching network



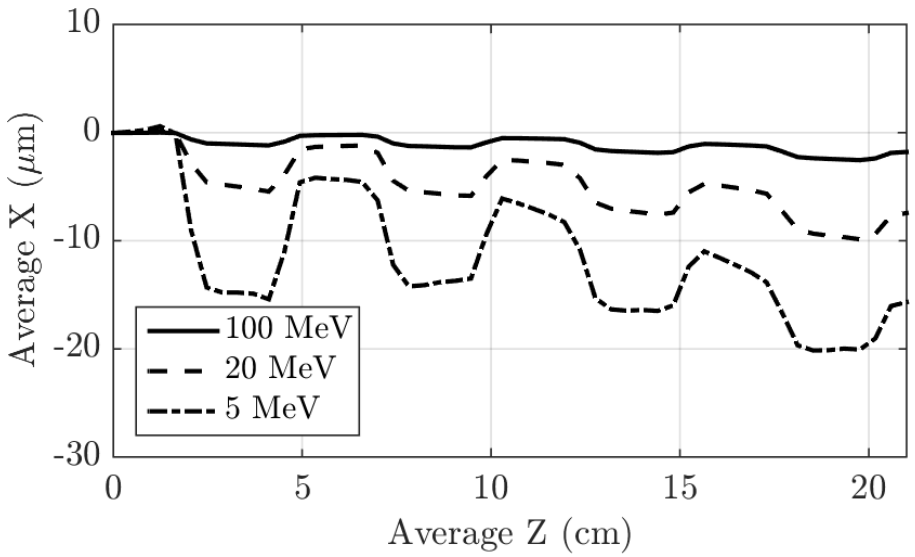
(a) (b)

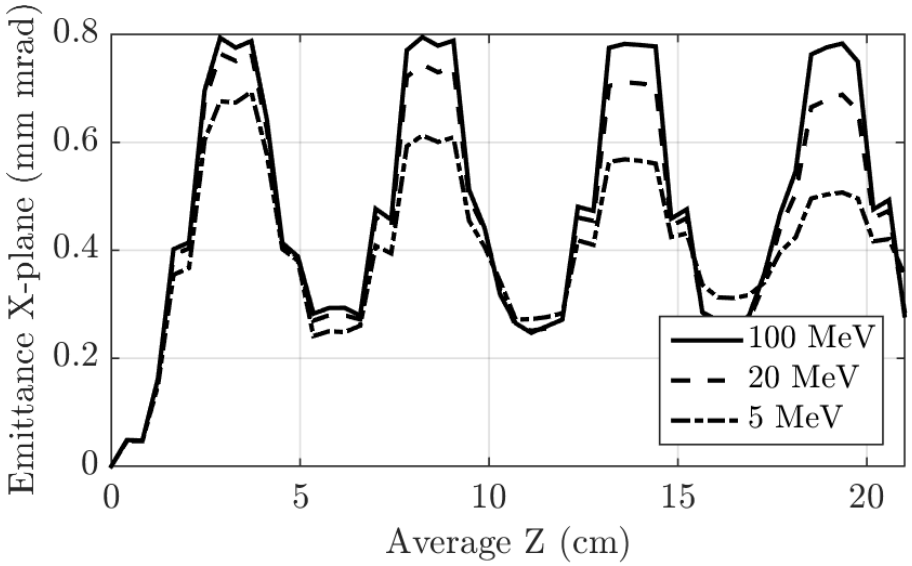
J. Navarro, Breakdown studies for high gradient RF warm technology in: CLIC and hadron therapy linacs, Ph.D. thesis.

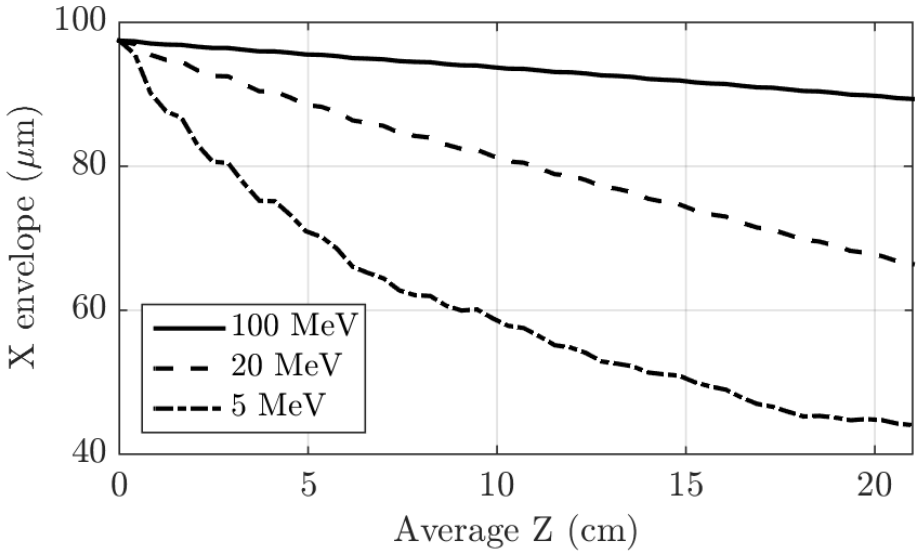
Parameters	Clic-G T24	Parallel Coupling
Unloaded gradient (MV/m)	100	81.7
Input/Output radii (mm)	3.15/2.35	1.00
Group velocity (%c)	1.79/0.91	63
Shunt impedance (MΩ/m)	116/150	161
Peak Input Power (MW)	75	41.5
Filling time (ns)	57	5
Maximum E-Field (MV/m)	222	272
Maximum modified Poynting vector	3.51	3.99
Maximum pulse heating temperature rise	14	23

Beam Dynamics 1/2

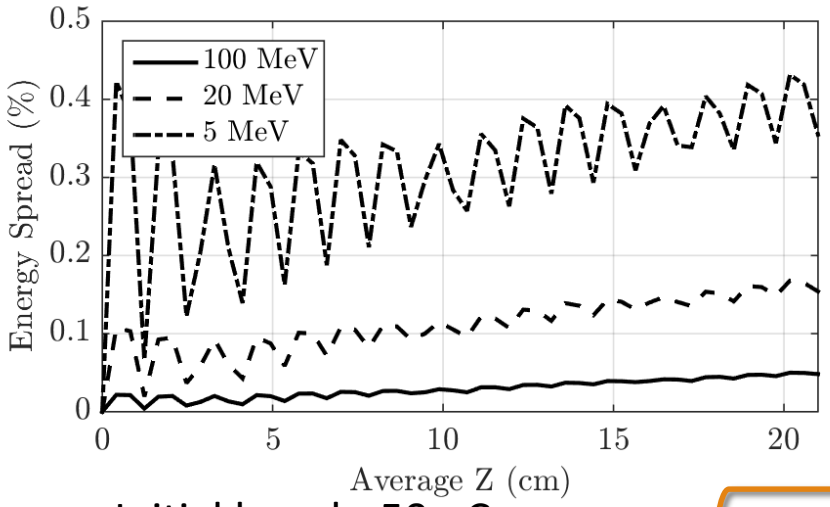
The presence of one sided coupling holes for each leads to a dipolar kicks. This one is compensated every two cells but the longitudinal momentum is minimum at the beginning of the section, so the compensation effect is not perfect. The offset angles are 9.5, 38 and 95 µrad in the x-plane and 9.5, 47 and 120 µrad in the y-plane for a bunch injected in the axis with initial energy of 100, 20 and 5 MeV respectively and a charge of 50 pC.







Beam Dynamics 2/2



The electron bunch boosted through the PCAS has a good quality, emittance < 1 mm mrad, energy spread < 0.1%.

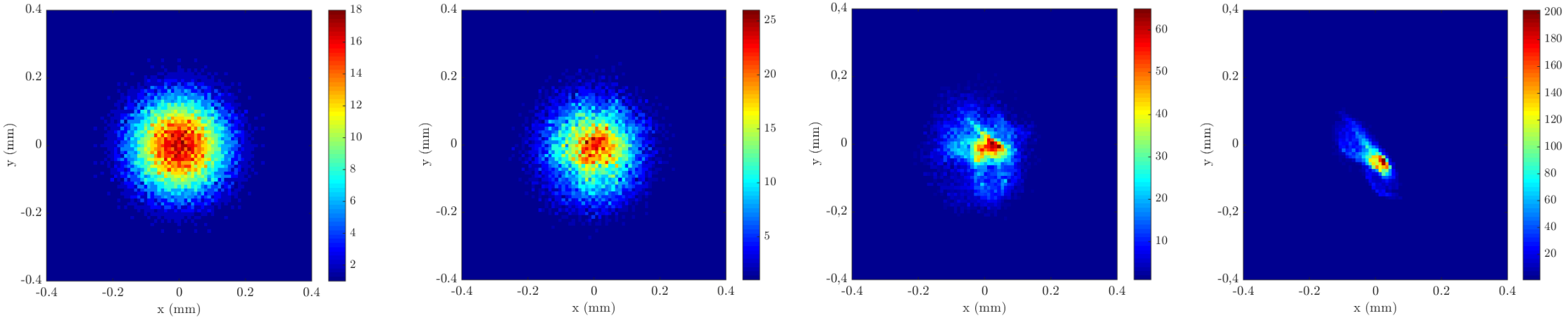
Final Spot Bunch

Initial bunch: 50 pC zero emittance and energy spread

100 MeV initial energy

20 MeV initial energy

5 MeV initial energy



Future development

1. *Compensation of the dipolar kick through a symmetric feeding interpolation scheme*
2. *Improved design taking into account the mechanical constraint (cooling).*