FAST BEAM-ION INSTABILITIES

Vacuum Specifications in CLIC Main Linac

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Outline

1. Introduction
    - Fast Beam-Ion Instability
    - Field Ionization
    - FASTION & Application to CLIC
2. Results of Pressure Scans
    - Summary of Frequency Analysis & Single Gas Species
    - Different Main Linac Designs
    - Parameter Scans
3. Conclusion

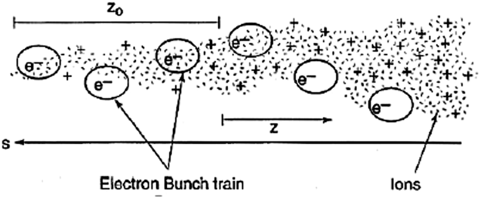
Fast Beam-Ion Instability I

Fast beam-ion instability (FBII):

- electron bunches create ions out of residual gases by
  - scattering ionization
  - field ionization – exceeding threshold (beam transversely small enough)
- electromagnetic interaction between electrons and ions
  - ions created bunch by bunch and kicked by passing bunches
  - electron bunches feel effect of ion field
- resulting in
  1. extra phase advance shift over bunch train
  2. possible excitation of unstable ion-electron coupled motion (ions do not necessarily need to be trapped)

Fast Beam-Ion Instability II

- two-stream instability:
  - accumulation of ions around beam for long enough times $\Longrightarrow$ coupled oscillations between electrons and ions triggered (resonance, grows by its own)



source: http://sps-impedance.web.cern.ch/sps-impedance/USPAS/TwoStream.pdf

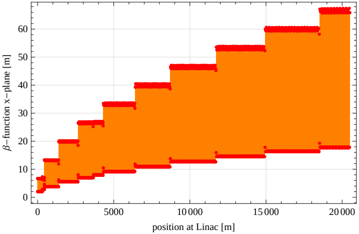
Shrinking Transverse Beam Size I

- acceleration of beam causes shrinking transverse size $\sigma_{x,y}$:

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}(s) \cdot \beta_{x,y}(s)}$$

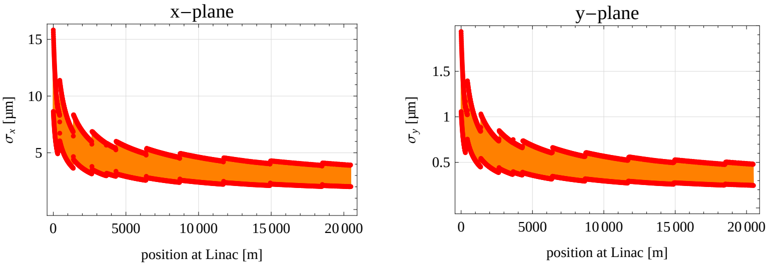
- geometric emittances shrink since $\epsilon_{x,y} = \frac{\epsilon_{norm,\ x,y}}{\gamma}$
- β-functions increase along Main Linac with $\beta_{x,y} \approx \sqrt{\gamma}$ to partially compensate
- thus we see

$$\sigma_{x,y} \propto \gamma^{-\frac{1}{4}}$$



Shrinking Transverse Beam Size II

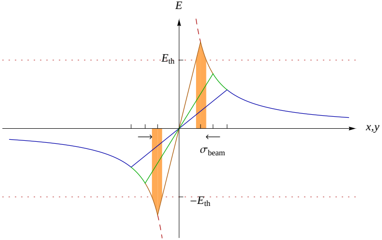
$$\sigma_{x,y} \propto \gamma^{-\frac{1}{4}}$$



- field ionization can start (threshold transverse beam size)
- trapping condition changes along Main Linac
  (classical trapping only occurs at the very beginning)
- excited frequencies different along Main Linac

Field Ionization

- peak electric field rises with shrinking transverse beam size
- residual gases are ionized in area where electric field exceeds gas-specific thresholds



Gas Species	ξ [eV]	E_{th} [GV/m]
H_2	15.4	26
H_2O	12.6	18.5
CO	14.0	22
CO_2	13.8	21.5

FASTION code

FASTION code produces several output files, e.g.

- bunch by bunch offsets x, x', y, y' over whole train for all lattice points

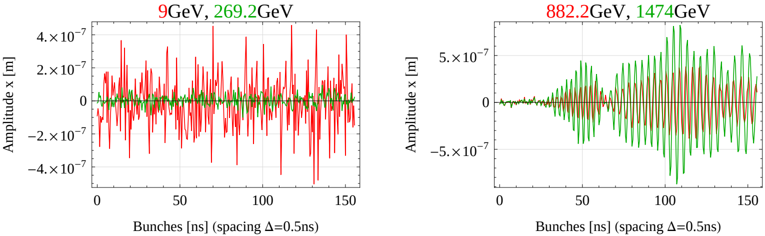


Figure: Bunch offsets – ion species: H_2O, pressure: 20nTorr

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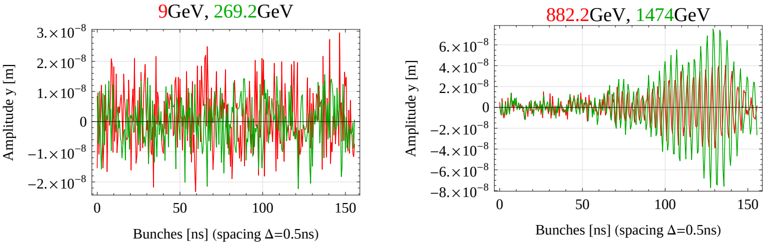

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- sample ion trajectories recorded uniformly distributed

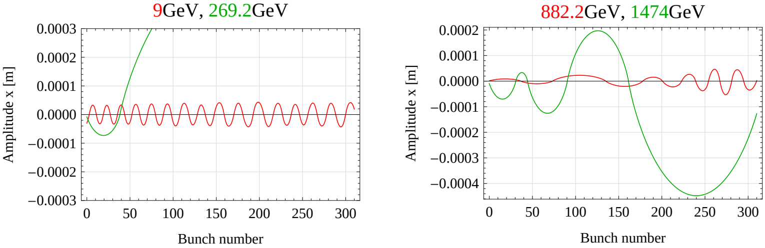

Figure: Ion trajectories – ion species: H_2O, pressure: 20nTorr

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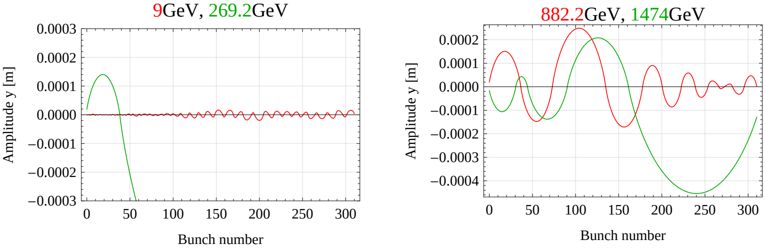


Figure: Ion trajectories – ion species: H_2O, pressure: 20nTorr

Specifications

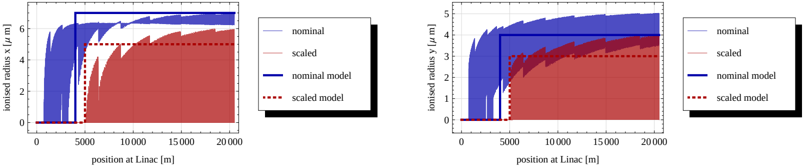
Parameters used in the study of CLIC Main Linac:

parameter	*symbol*	*nominal version*	*scaled version*	*different lattice version*
Energy	p_0 [GeV]	9 to 1500	9 to 500	9 to 250
Normalized transverse emittance	$\epsilon_{x,y}$ [nm]	660, 10	660, 10	660, 10
Bunch population	N	4×10^9	1.33×10^9	6.8×10^9
Number of bunches	N_b	312	1248	354
Bunch spacing	ΔT_b [ns]	0.5	0.5	0.5
Bunch length	σ_z [ps]	0.15	0.15	0.15
Main Linac length:	L [km]	20.5	20.5	4.5
Gas pressure	P [nTorr]	scanned	scanned	scanned
Scattering ionization cross section	σ_{ions} [MBarn]	2	2	2
Threshold of the electric field	E_{th} [GV/m]	18	18	18

Field Ionization Area

- field ionization occurs differently depending on the lattice
- scaled and alternative Linac design: field ionization only appears in the horizontally defocussing magnets (since $E_{max} \propto \dfrac{1}{\sigma_x}$)

Nominal 1.5 TeV and scaled 500 GeV Linac:



Field Ionization Area

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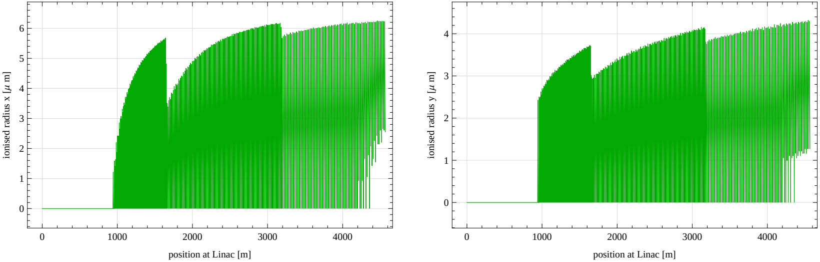
- scaled and alternative Linac design: field ionization only appears in the horizontally defocussing magnets (since $E_{max} \propto \frac{1}{\sigma_x}$)

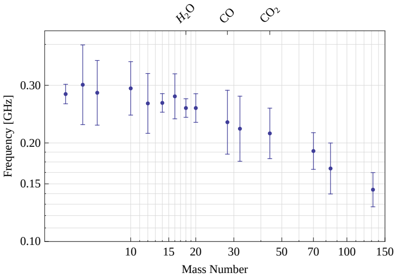
Alternative 250 GeV Linac:



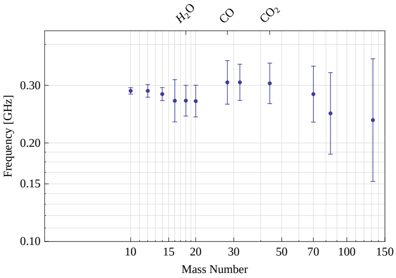
Frequency Analysis at 20nTorr

- evaluation of frequency dependencies on ion mass number
- upcoming unstable resonance frequencies at $A = 5$, clear beam instability from $A = 7$ on (20nTorr)
- frequency mean values and standard deviation:

x-plane



y-plane



Single Gas Species

- analysed pressure thresholds of single gas species
  - fourier spectrum of bunch centroids at the end of Linac, maximum mode grows out of noise at pressure threshold
- main gas components yield:
  - H_2 stable at least until 200nTorr ($\Rightarrow$ above considered pressure range)
  - H_2O becomes unstable from 4nTorr on
  - CO becomes unstable from 3nTorr on
  - CO_2 becomes unstable from 2nTorr (x-plane) and 3nTorr (y-plane) on

Composition of Vacuum

- analysed three different vacuum compositions:

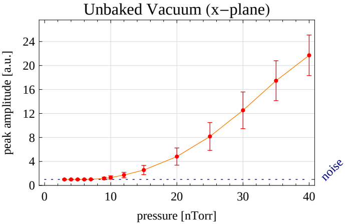
	Unbaked Vacuum	Baked Vacuum	Baked Vacuum With NEG Pumping
H_2	40%	80%	90%
H_2O	40%	10%	4%
CO	10%	5%	3%
CO_2	10%	5%	3%

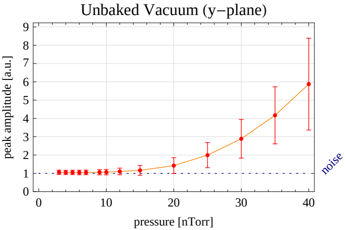
Thanks to S. Calatroni for providing the compositions

- total pressure fixed where H_2 part neglected in gas mixture simulations (i.e. Baked & NEG @ 40 nTorr $\widehat{=}$ 1.6 nTorr H_2O + 1.2 nTorr CO + 1.2 nTorr CO_2)

Nominal CoM Energy 3 TeV

- constant field ionization from 4 km onwards

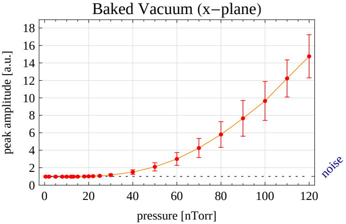

Unbaked Vacuum (x−plane)

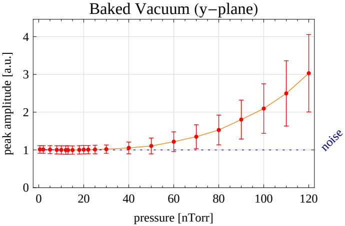

Unbaked Vacuum (y−plane)

- unbaked vacuum unstable above 7-8 nTorr

Nominal CoM Energy 3 TeV

- constant field ionization from 4 km onwards

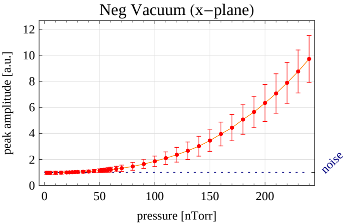


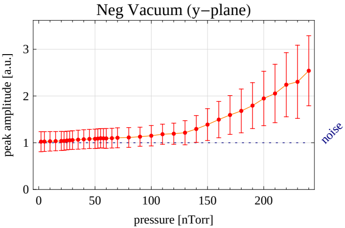


- unbaked vacuum unstable above 7-8 nTorr
- baked vacuum unstable above 20-25 nTorr

Nominal CoM Energy 3 TeV

- constant field ionization from 4 km onwards

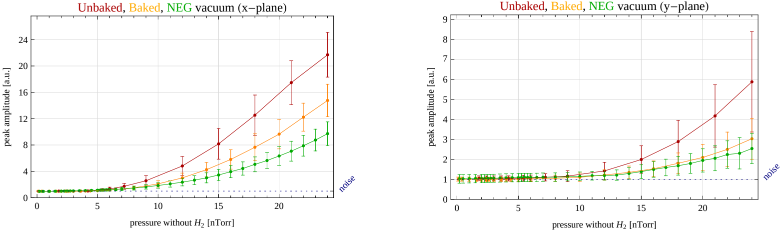




- unbaked vacuum unstable above 7-8 nTorr
- baked vacuum unstable above 20-25 nTorr
- baked vacuum with NEG unstable above 50 nTorr

Nominal CoM Energy 3 TeV

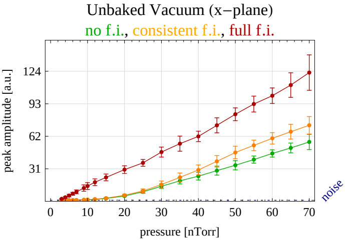
- constant field ionization from 4 km onwards



- unbaked vacuum unstable above 7-8 nTorr
- baked vacuum unstable above 20-25 nTorr
- baked vacuum with NEG unstable above 50 nTorr
- comparing "active" part: NEG most stable

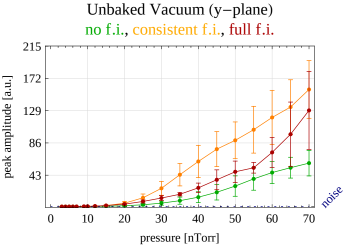
Scaled CoM Energy 1 TeV

- at first, scaled lattice with nominal parameters studied
- three different field ionization models



Unbaked Vacuum (x−plane)

no f.i., consistent f.i., full f.i.

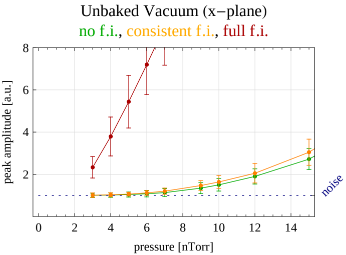


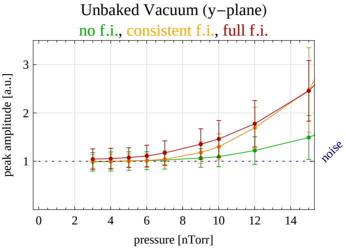
Unbaked Vacuum (y−plane)

no f.i., consistent f.i., full f.i.

Scaled CoM Energy 1 TeV

- at first, scaled lattice with nominal parameters studied
- three different field ionization models





- unbaked vacuum unstable above x: 5 nTorr, y: 6-7 nTorr
- baked vacuum unstable above x: 15 nTorr, y: 20-25 nTorr
- NEG unstable above x: 30-40 nTorr, y: 40-50 nTorr

Scaled CoM Energy 1 TeV

- scaled version with nominal parameters more critical than nominal lattice
- thereafter, different parameters (bunch population $N/3$ and bunch number $4 \times N_b$)
- now FBII occur at even lower pressures:
    - unbaked vacuum unstable above x: 3 nTorr, y: 5 nTorr
    - baked vacuum unstable above x: 8 nTorr, y: 15 nTorr
    - NEG unstable above x: 20 nTorr, y: 30 nTorr

Alternative CoM Energy 500 GeV

- at first, alternative lattice with nominal parameters studied
- completely self-consistent field ionization model
- alternative lattice less prone to FBII than nominal lattice:
    - unbaked vacuum unstable above 20 nTorr
    - baked vacuum unstable above 60 nTorr
    - NEG unstable above 110-120 nTorr
- likewise, weaker amplification of the instable motion

Alternative CoM Energy 500 GeV

- correct design values are
  - increased bunch number $N_b = 354$ (instead of 312)
  - increased bunch population $N = 6.8 \times 10^9$ (instead of 4×10^9)
- stronger FBII in horizontal plane are encountered, vertical plane is not affected at all:
  - unbaked vacuum unstable above x: 10 nTorr, y: 20 nTorr
  - baked vacuum unstable above x: 30 nTorr, y: 60 nTorr
  - NEG unstable above x: 60 nTorr, y: 110-120 nTorr

$\Rightarrow$ horizontal thresholds lowered by 50%!

Parameter Scans

- concentration on nominal 3 TeV lattice
- pressure scans while changing a few other parameters as
  - bunch spacing $\Delta T_b = 1$ ns (doubled) and bunch number $N_b = 156$ (halved)
  - bunch charge $N = 1...9 \times 10^9$ (nominal value 4×10^9)
  - horizontal emittance $\epsilon_x = 330, 660, 1320$ nm (nominal value 660 nm)
  - vertical emittance $\epsilon_y = 5, 10, 30, 50$ nm (nominal value 10 nm)

Parameter Scans

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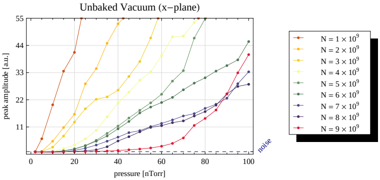
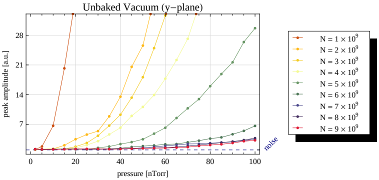
- pressure scans while changing a few other parameters as
  - bunch spacing $\Delta T_b = 1$ ns (doubled) and bunch number $N_b = 156$ (halved)
  - bunch charge $N = 1 ... 9 \times 10^9$ (nominal value 4×10^9)
  - horizontal emittance $\epsilon_x = 330, 660, 1320$ nm (nominal value 660 nm)
  - vertical emittance $\epsilon_y = 5, 10, 30, 50$ nm (nominal value 10 nm)
- double bunch spacing and halved bunch number yield
  - no vertical instabilities
  - horizontal instabilities appear at
    - unbaked vacuum: 15 nTorr
    - baked vacuum: 45-50 nTorr
    - baked vacuum and NEG pumping: 80-90 nTorr

Bunch Charge Scan

- bunch charge scanned as $N = 1...9 \times 10^9$ (nominal value 4×10^9)
- first run of simulations: field ionization model fixed

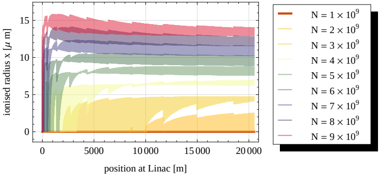


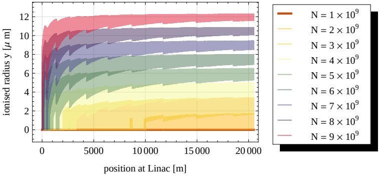


- lower bunch charge means ions get less overfocussed

Bunch Charge Scan

- bunch charge scanned as $N = 1 \ldots 9 \times 10^9$ (nominal value 4×10^9)
- first run of simulations: field ionization model fixed
- field ionization inset and area varies significantly





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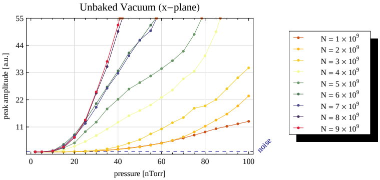
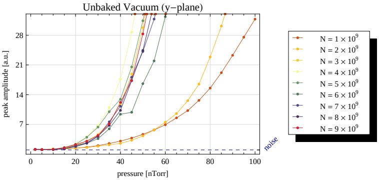
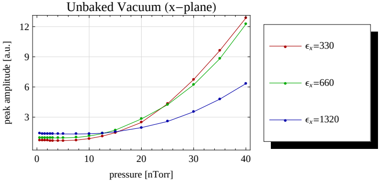


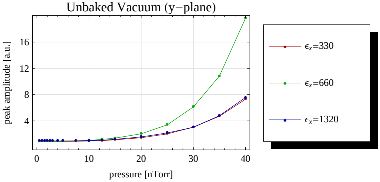


- lower bunch charge means ions get less overfocussed
- situation reversed, lowest bunch charge is best now

Horizontal Emittance Scan

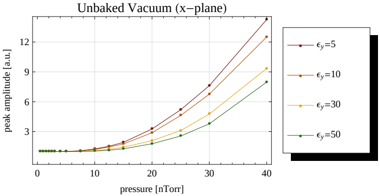
- horizontal emittance scanned as $\epsilon_x = 330, 660, 1320$ nm (nominal value 660 nm)

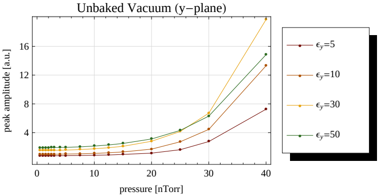




Vertical Emittance Scan

- vertical emittance scanned as $\epsilon_y = 5, 10, 30, 50$ nm (nominal value 10 nm)


Unbaked Vacuum (x−plane)


Unbaked Vacuum (y−plane)

Conclusion

- for combinations of gas species, thresholds more relaxed

Vacuum Composition	Nominal 3 TeV	Scaled 1 TeV		Alternative 500 GeV	
		$N_b = 312$ $N = 4e9$	$N_b = 1248$ $N = 1.33e9$	$N_b = 312$ $N = 4e9$	$N_b = 354$ $N = 6.8e9$
Unbaked	7-8 nTorr	5 nTorr	3 nTorr	20 nTorr	10 nTorr
Baked	20-25 nTorr	15 nTorr	8 nTorr	60 nTorr	20 nTorr
Baked and NEG pumped	50 nTorr	30-40 nTorr	20 nTorr	110-120 nTorr	∼60 nTorr

- doubled interbunch spacing and halved bunch number
  ⇒ thresholds about two times as high as nominal ones
- bunch charge scan shows that fully ionized area grows with increasing bunch populations
  ⇒ horizontally, beam is more stable with diminishing bunch charge, $N = 1 \times 10^9$ is best case (since no f.i.)