Beam Breakup and High Order Modes Instabilities Studies for Energy Recovery Linear Accelerators

Sanae SAMSAM | PhD School: FISICA DEGLI ACCELERATORI

SAPIENZA UNIVERSITÀ DI ROMA

INFN MILANO Istituto Nazionale di Fisica Nucleare Sezione di Milano

Supervisor:
Luca Serafini

Outline

Part 1
Thesis Overview & Motivation

Part 2
BriXSinO

Part 3
Technology of Superconducting Cavities

Part 4
The Theory of HOMEN Model

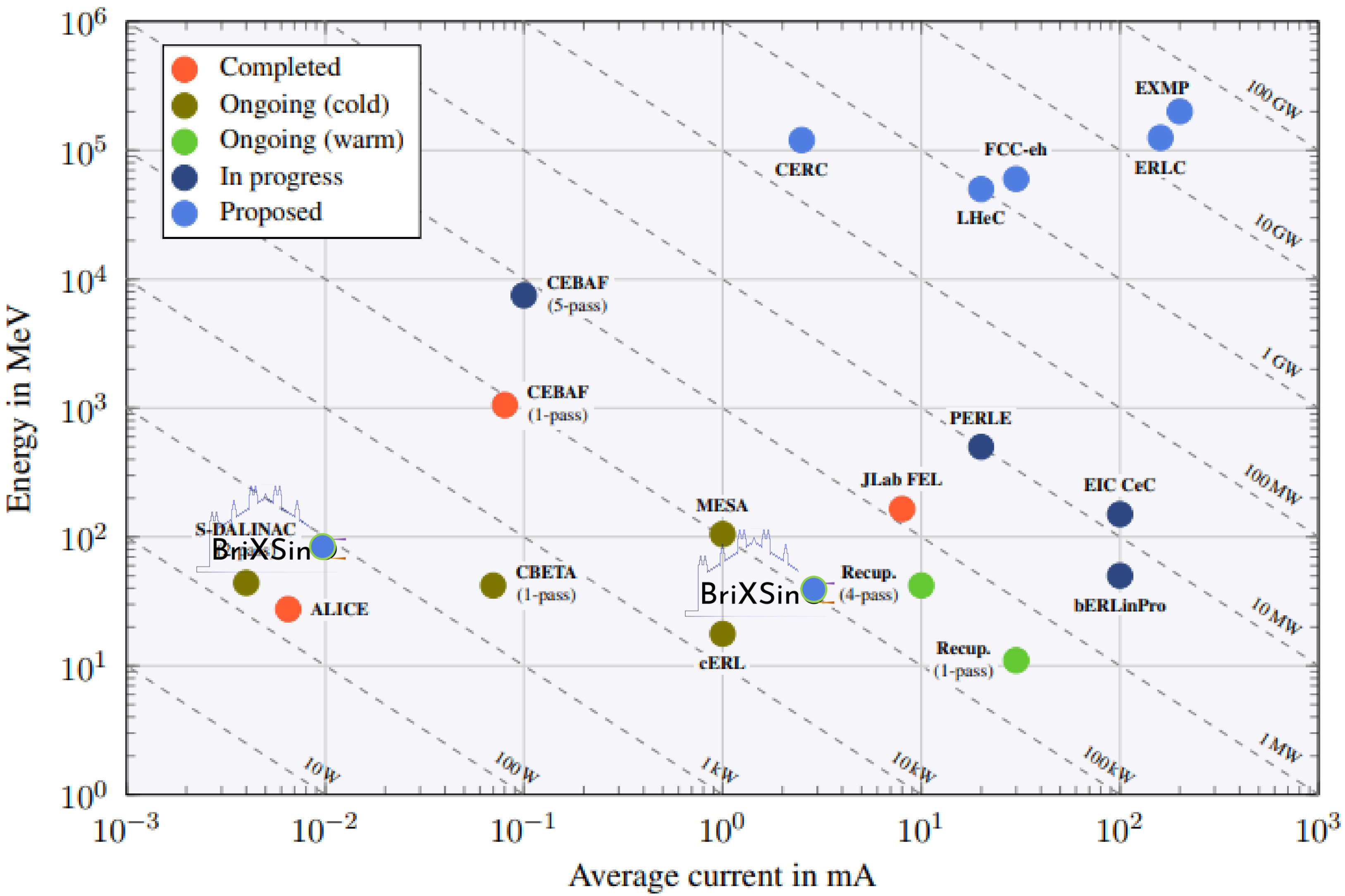
Part 5
High order modes Excitation and Damping

Part 6
The Compact HOMEN

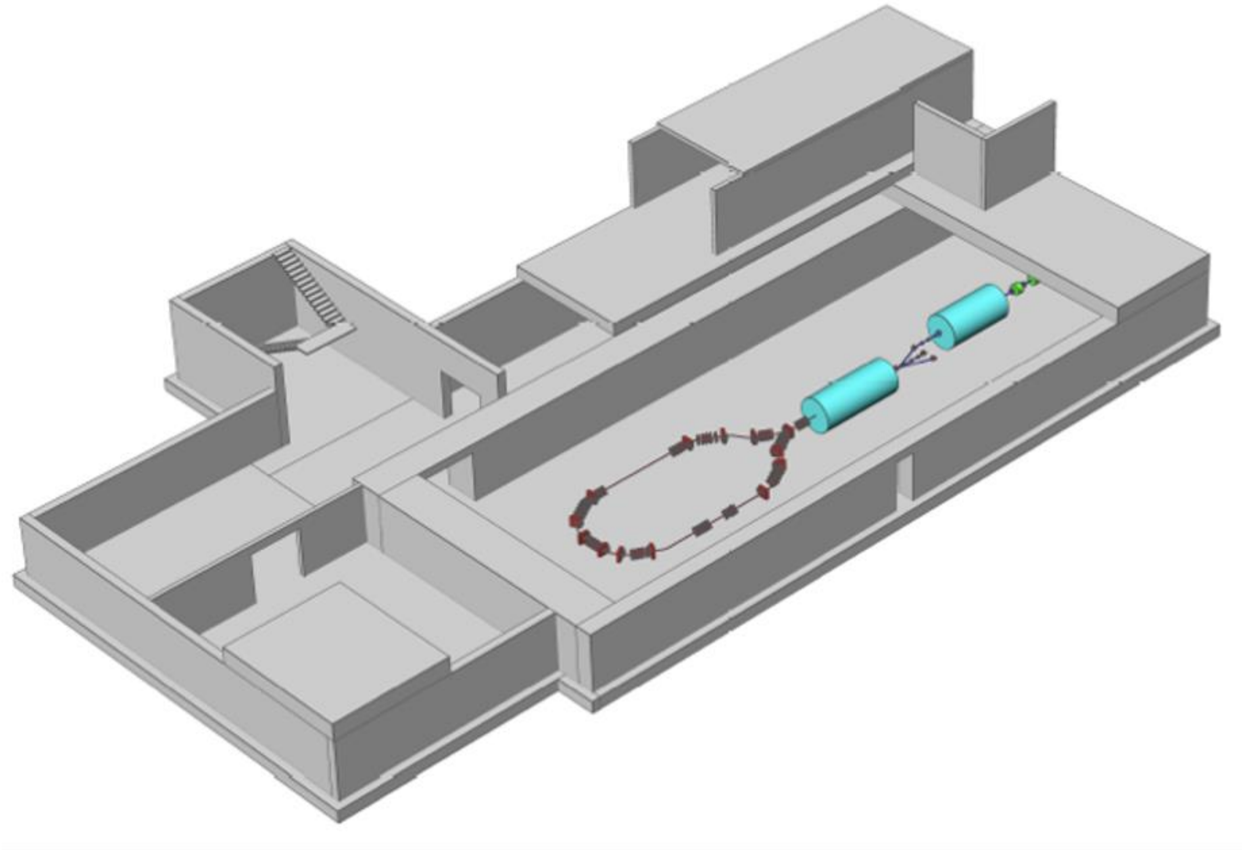
Part 7
Summary & Outlook

Motivation:

- Electron beams with large average current (mA) and high repetition rate
- Linacs with energy recovery → ERL
- Interaction of electron beams with accelerator cavities (HOMs instabilities…)



Brilliant source of ***X***-rays based on ***S***ustainable and ***in***n***O***vative accelerators



LASA aerial view and rendering of the building

Istituto Nazionale di Fisica Nucleare

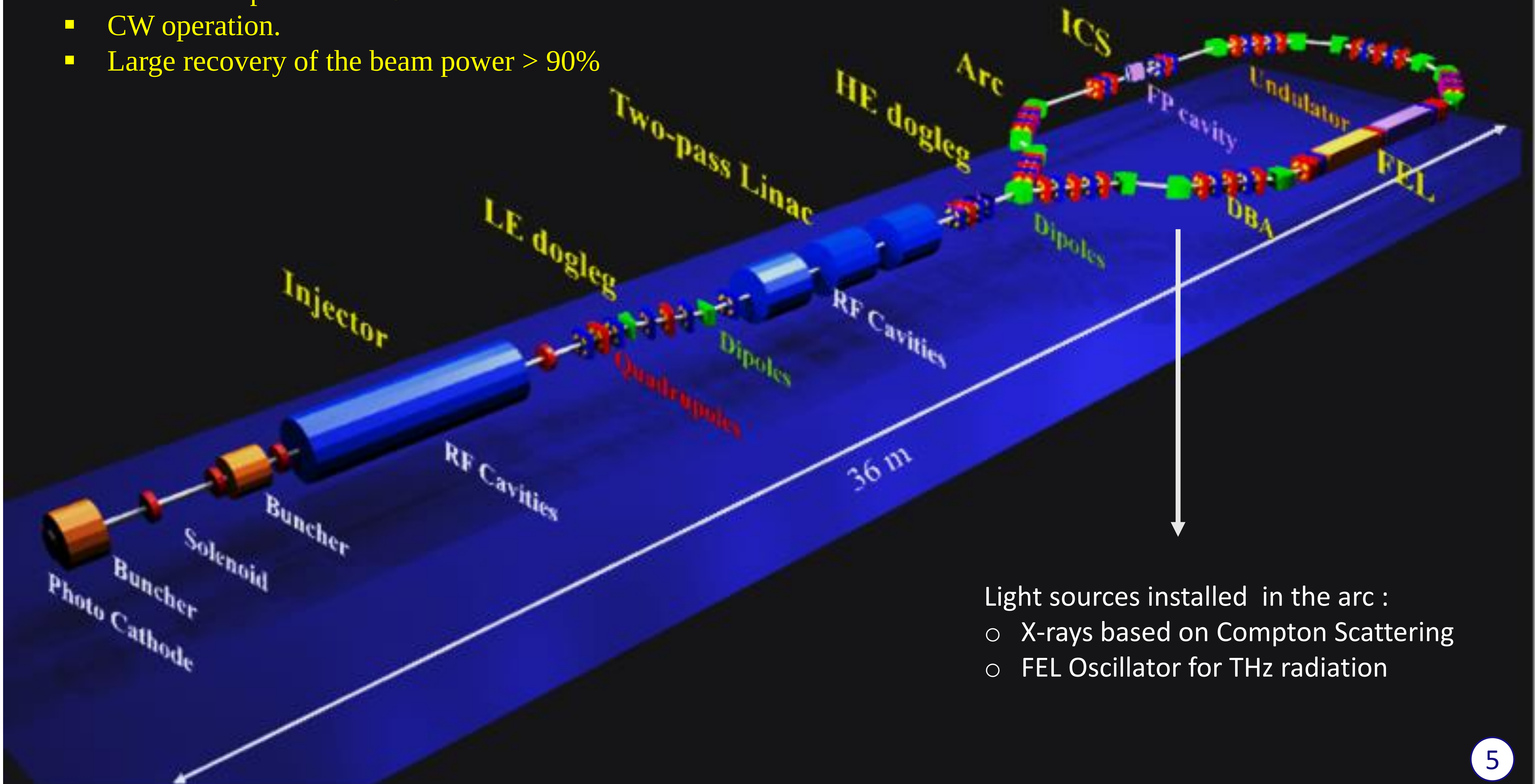
UNIVERSITÀ DEGLI STUDI DI MILANO

BriXSinO

Brilliant source of X-rays based on Sustainable and innOvative accelerators

Un acceleratore di elettroni innovativo verso la frontiera dell'alta intensità sostenibile, per i futuri acceleratori di particelle di larga scala, e per applicazioni avanzate con raggi X mono-cromatici e radiazione THz coerente

- 5 mA of average cuurent.
- 100 MHz repetition rate.
- CW operation.
- Large recovery of the beam power > 90%



Last year seminar

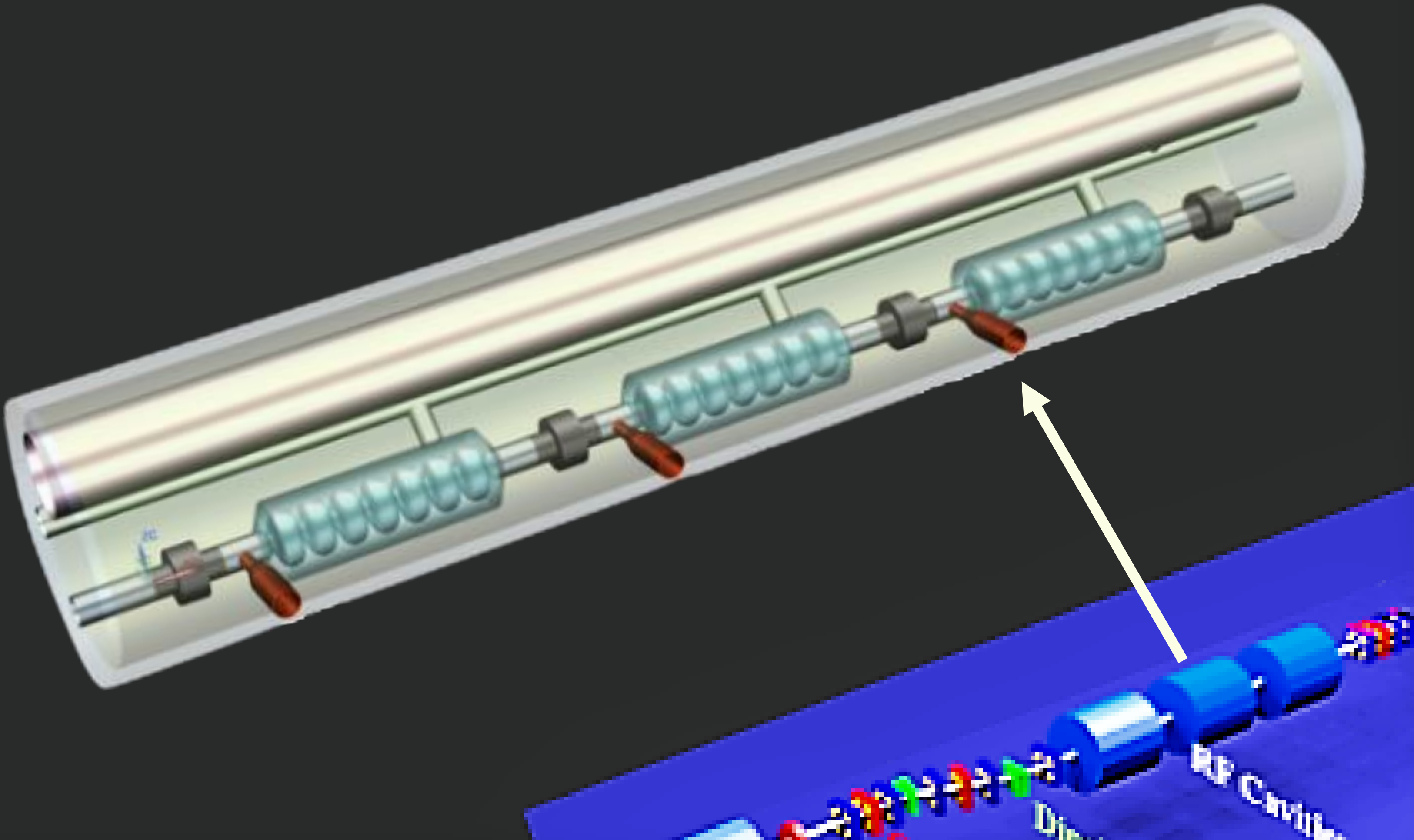
Light sources installed in the arc :

- X-rays based on Compton Scattering
- FEL Oscillator for THz radiation

The ERL Cryomodule

Parameter	Value
Type Of Accelerating Structure	**SW**
Accelerating Mode	**TM_{010} π-mode**
Fundamental Frequency [MHz]	**1300**
Design Gradient [MV/m]	**16.5**
Intrinsic Quality Factor Q_0	**$2X10^{10}$**
Loaded Quality Factor Q_{EXT}	**$3.25X10^{7}$**
Active Length [m]	**0.81**
Cell to cell coupling [%]	**2.2**
R/Q [Ohm]	**774**
Geometric Factor G [Ohm]	**271**
E_{peak}/E_{acc}	**2.1**
B_{peak}/E_{acc} [mT/MV/m]	**4.2**

Two main working modes:
As ERL for light source at electrons energy ~ 50 MeV
And double acceleration ~ 100 MeV



Why SRF

R_s Surface resistance

- nΩ (SRF) versus mΩ (NC) → power losses in cavity are few 10 Watts versus MW! for same operating field and duty cycle (SRF readily allows **CW**)

Q_0 Quality factor

- Q_0 values are $10^9<Q_0<10^{11}$ (SRF) depending on temperature (and operating field) versus $Q_0 \approx 10^4$ level (NC)

R Shunt Impedance

- R = TΩ-level (SRF) vs. MΩ-level (NC)

HOMs will exhibit high shunt impedances in SRF cavities too.

Example:
For a cavity with HOM at f = 3 GHz, $Q_l = 10^5$
→HOM will oscillate for τ = 5.3 μs
→ 1.6 km of length.

=> For CW operation, so many subsequent particles will experience the field that the first bunch left behind.

HOMEN Model

High Order Mode Evolution based on Energy badget

In-game parameters:

- Power source
- Dissipation power
- Average Power for beam acceleration
- HOMs Power

$$P_{diss} = \frac{\omega_n U_n}{Q_n}$$

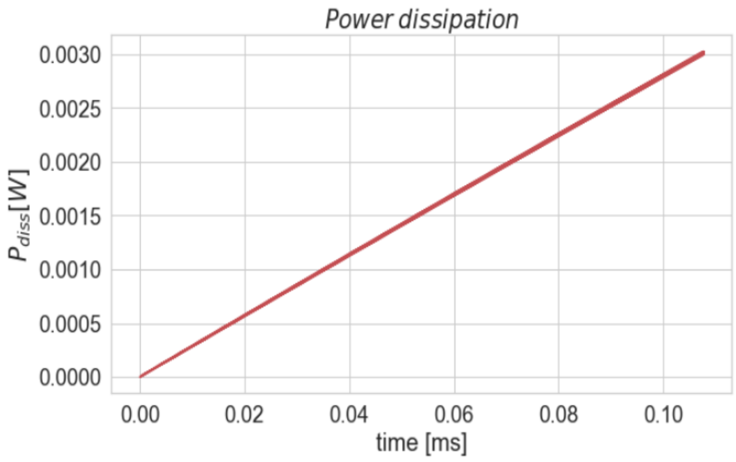
Example:

n → HOM

$\omega_n = 2\pi \times 2.63 \times 10^9$

$Q_n = 4.026 \times 10^7$

$U_0 = 0$



Theory and Modulation of HOMs

HOMEN's set of equations

Based on the concept of Energy Budget

The Stored Energy variation:

$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_{L,n}} + \delta_{1,n}\left|P_{\mathrm{kly}}\right| \pm \frac{q_i V_{acc_{n,i}}}{\tau_{cav}} + \frac{q_i^2 k_{loss,n}}{\tau_{cav}} \quad (1)$$

n: mode number

i: bunch number

q_i: Bunch charge

Mode Oscillation amplitude based on SVEA (Slowly Varying Envelope Approximation) :

$$\frac{dA_n}{dt} = \frac{A_n}{2U_n}\frac{dU_n}{dt} \quad (2)$$

$$\tau_{cav} = \frac{L_{cav}}{\beta(t_0)c}$$

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$$

Energy gain of the bunch:

$$\frac{d\gamma_n}{dt} = \frac{e}{m_0 c^2 \tau_{cav}} \sum_{n=1}^{N_{RF}} V_{acc_{n,i}} \quad (3)$$

Theory and Modulation of HOMs

HOMEN's set of equations

Based on the concept of Energy Budget

The Stored Energy variation:

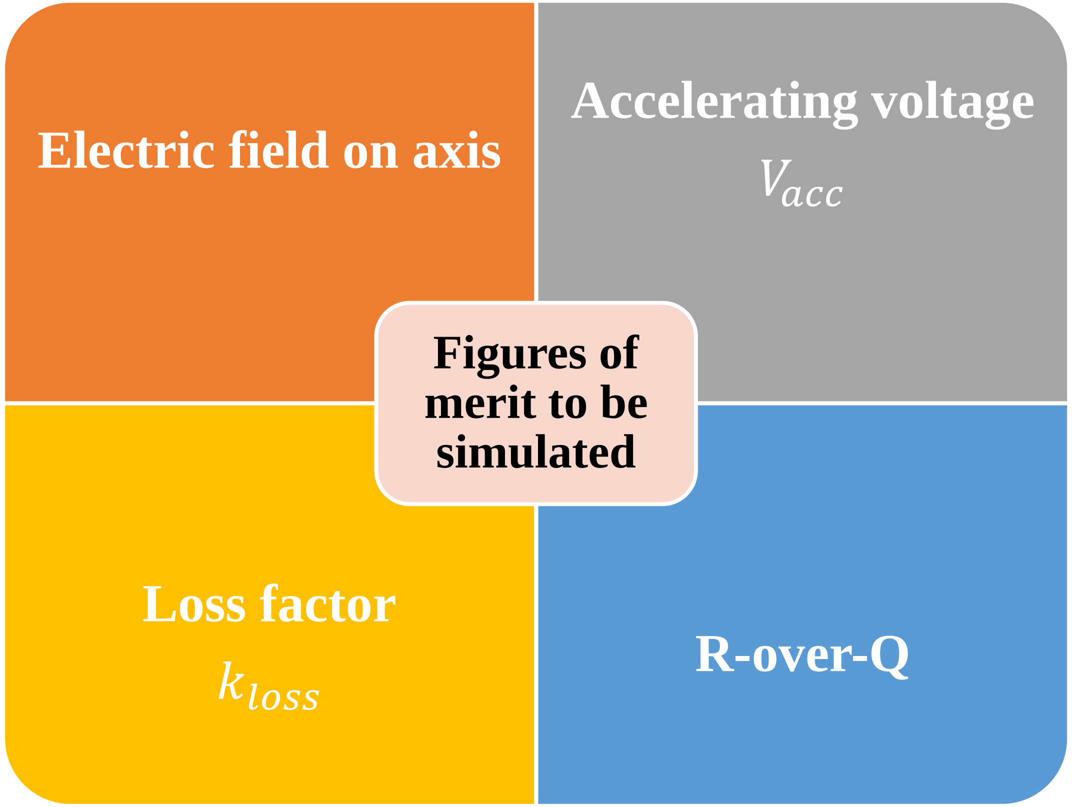
$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_{L,n}} + \delta_{1,n}\left|P_{\text{kly}}\right| \pm \frac{q_i V_{acc_{n,i}}}{\tau_{cav}} + \frac{q_i^2 k_{loss,n}}{\tau_{cav}}$$

Mode Oscillation amplitude based on SVEA:

$$\frac{dA_n}{dt} = \frac{A_n}{2U_n}\frac{dU_n}{dt}$$

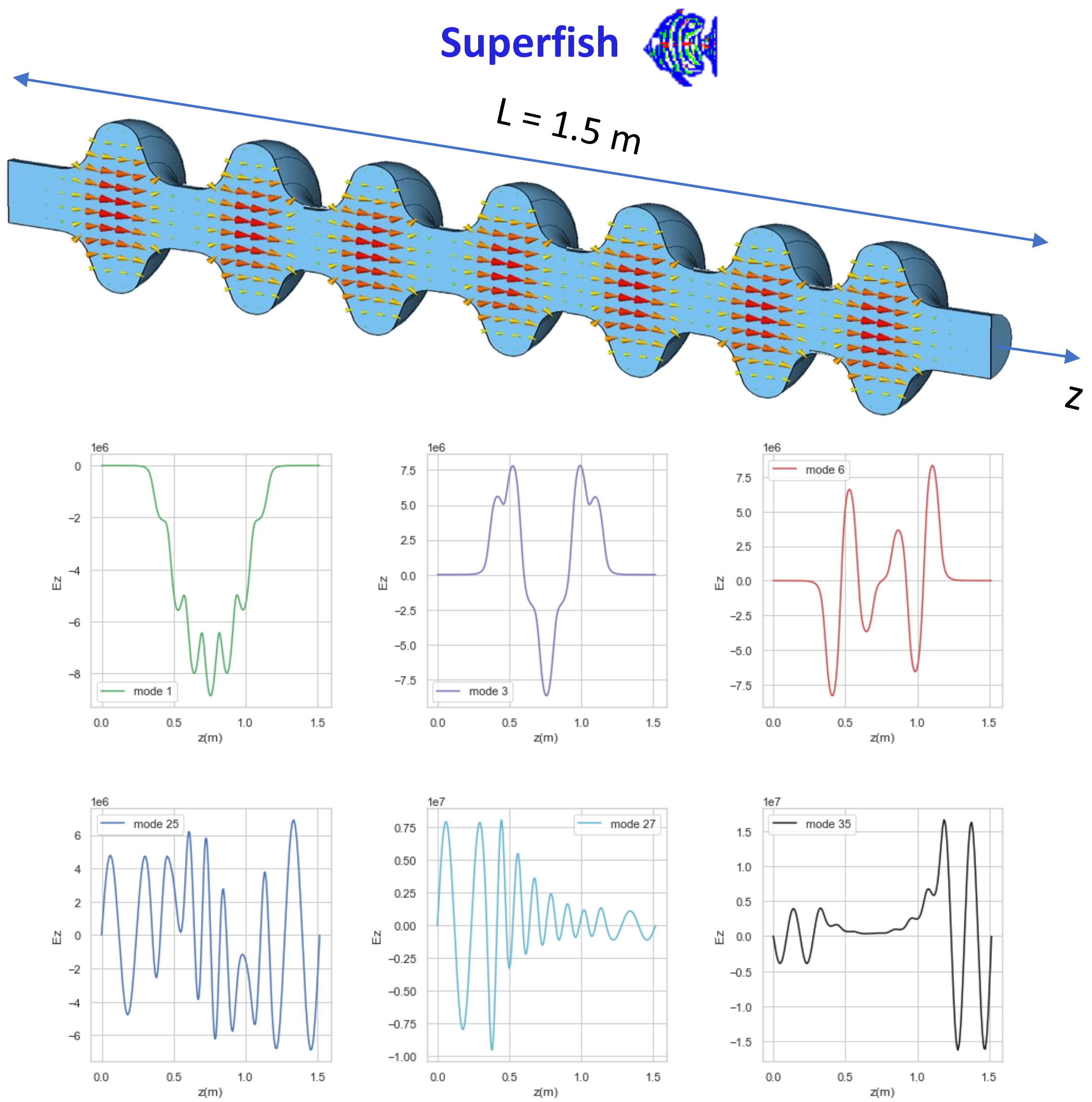
Energy gain of the bunch:

$$\frac{d\gamma_n}{dt} = \frac{e}{m_0 c^2 \tau_{cav}} \sum_{n=1}^{N_{RF}} V_{acc_{n,i}}$$



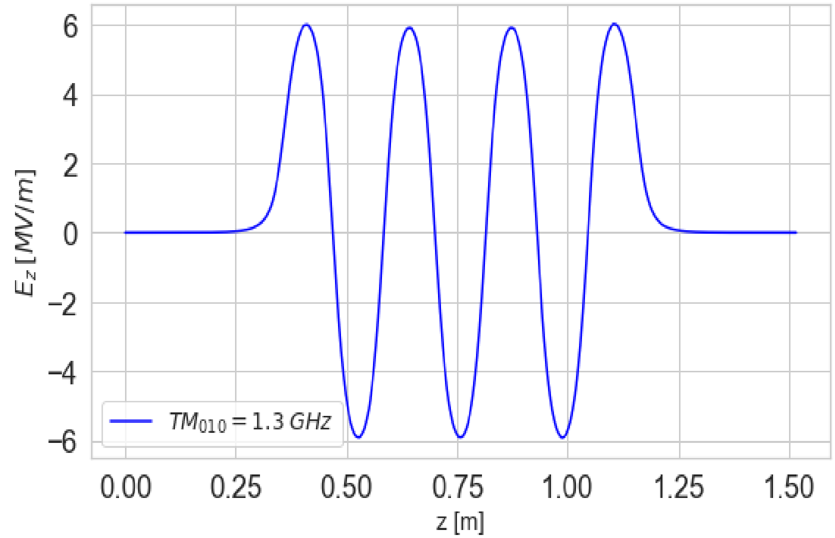
EM field

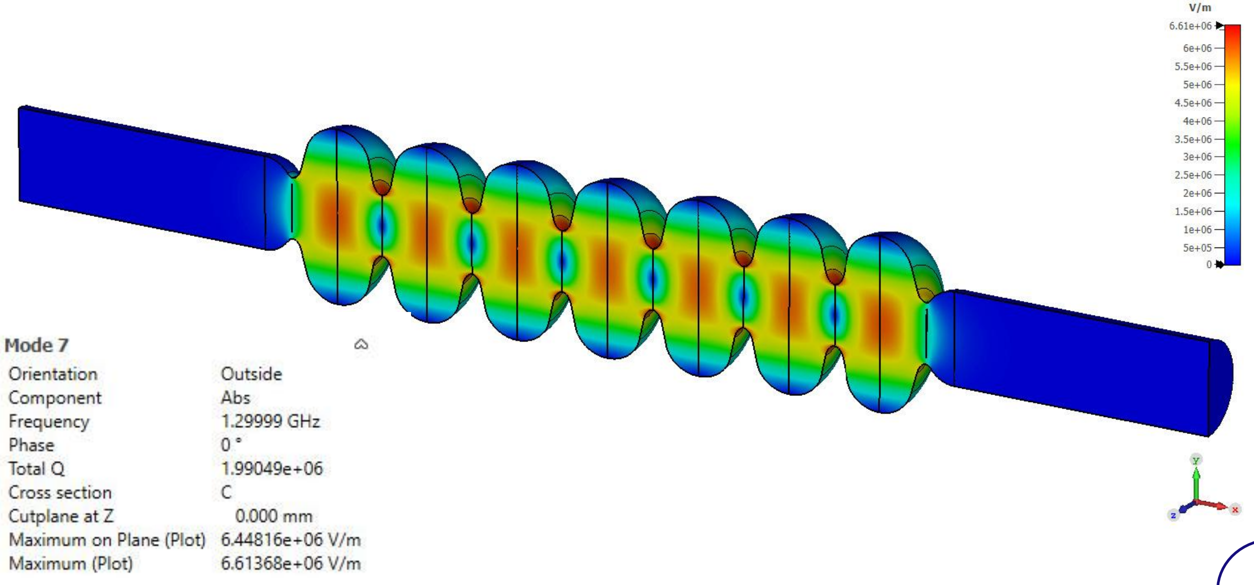
Simulated Parameters



EM field

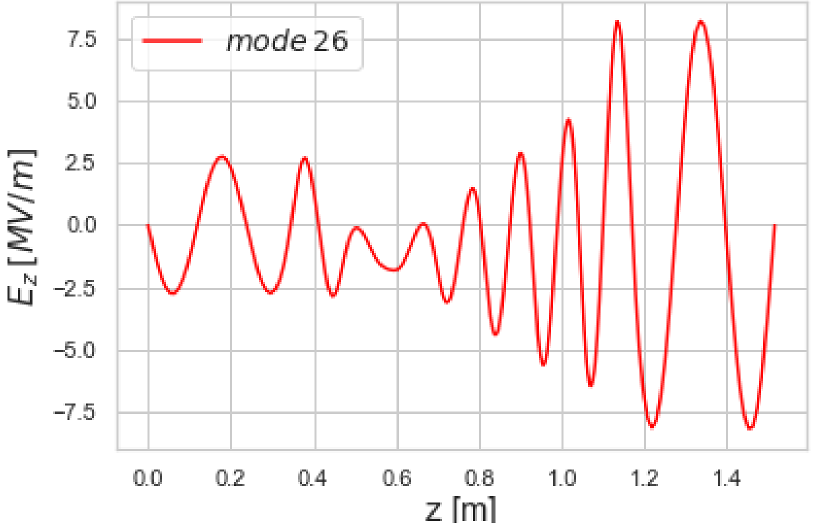
Simulated Parameters

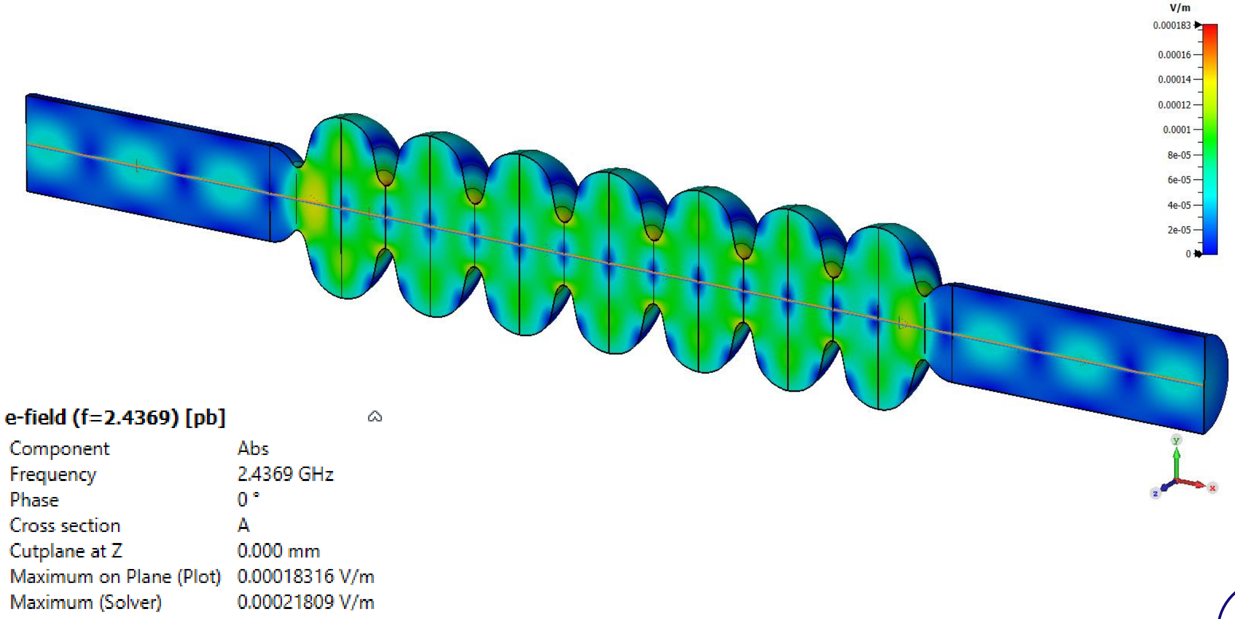




EM field

Simulated Parameters



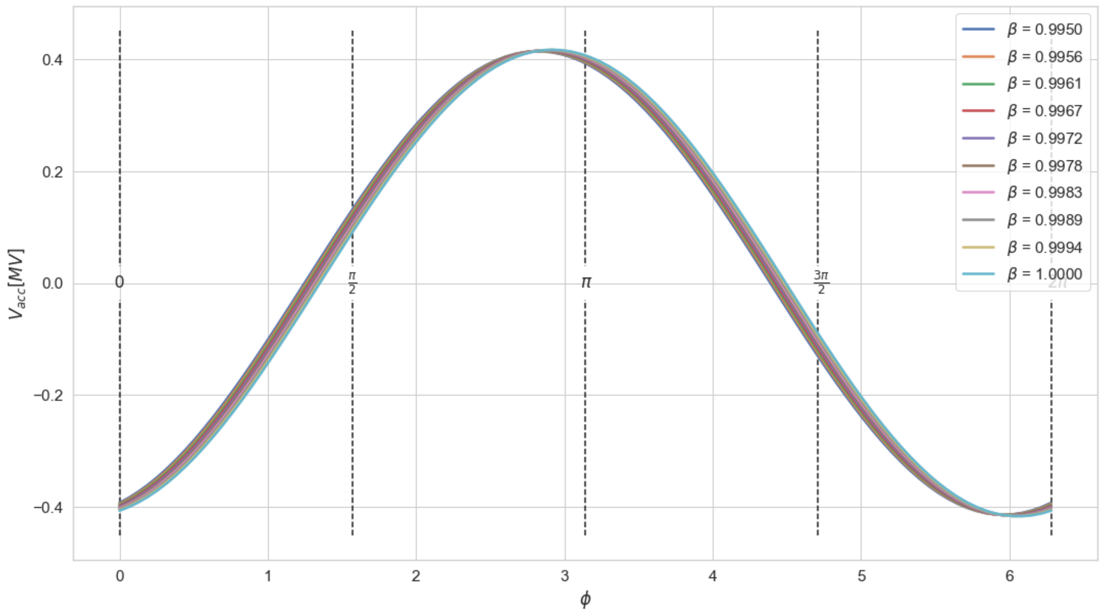


Simulated Parameters

Accelerating Voltage

$$V_{acc_{n,i}} = A_n(t) \int_0^{L_{cav}} e_n(z) \sin\left(\frac{\omega_n z}{\beta(t_{0,i})c} + \phi_{n,i}\right) dz$$

Spatial electric field



Methods:

- Simpson Integral 
- Quintic Interpolation method

Simulated Parameters

Loss factor k_{loss}

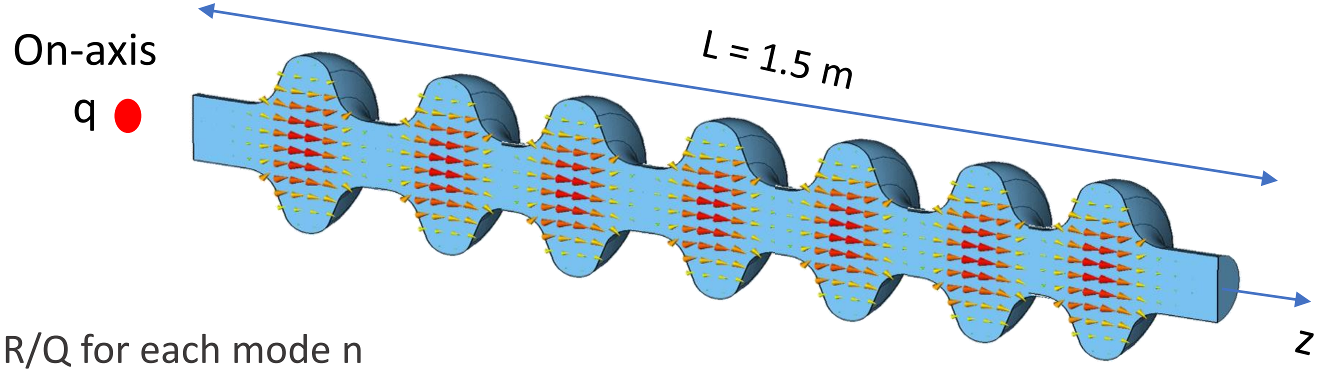
a measure of how efficiently the cavity transfers its stored energy to the beam passing through it.

$$k_{loss,n} = \frac{\Delta U}{q^2} = \frac{\omega_n}{2}\left(\frac{R}{Q}\right)_n$$

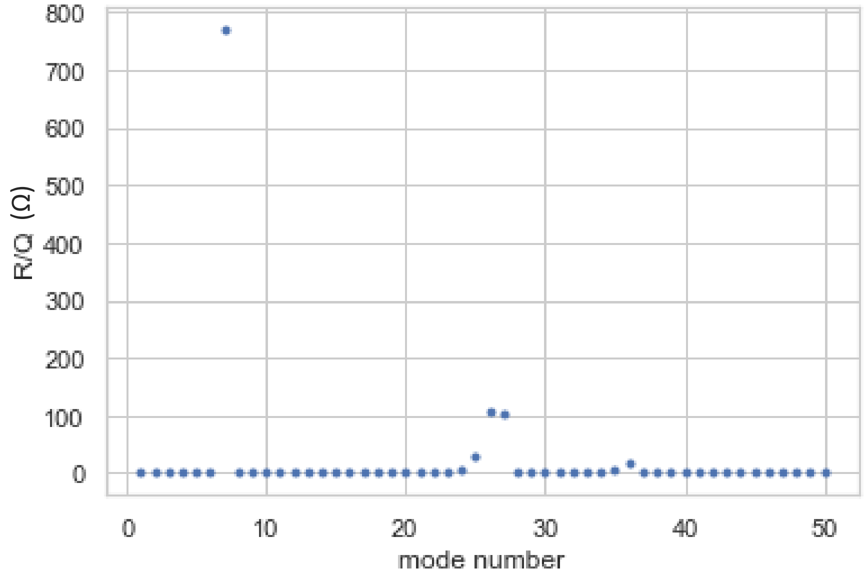
Point-like charge

Real bunch

Wakefield Potential integration



R/Q for each mode n



Simulated Parameters

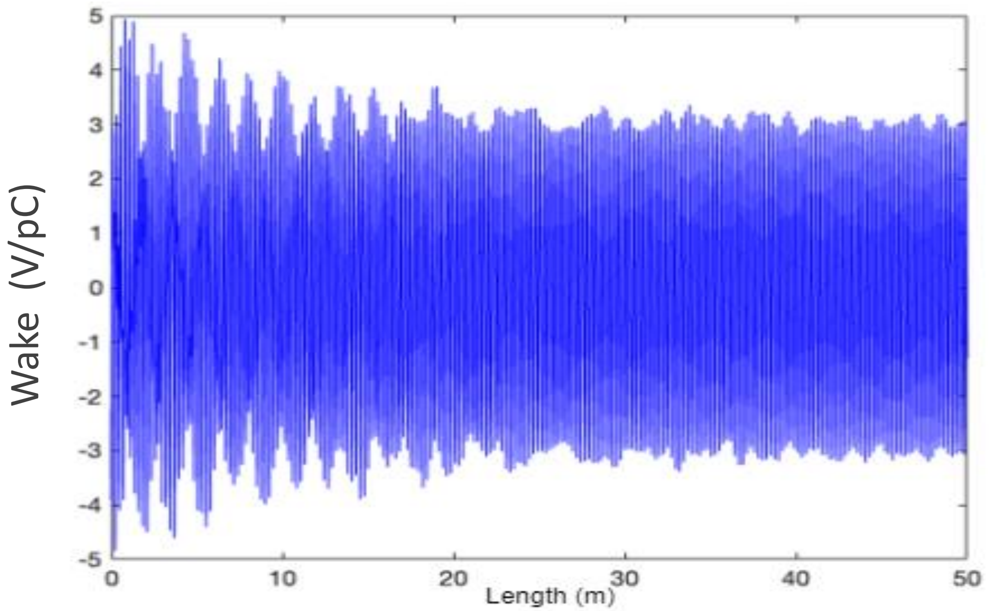
- $w(t) = \frac{\Delta U}{qq'}$
- $W(s) = \int_{-\infty}^{s} \lambda(s')w(s-s')ds'$ — Bunch length is considred
- $k_{loss} = \int_{-\infty}^{+\infty} \lambda(s)W(s)ds$

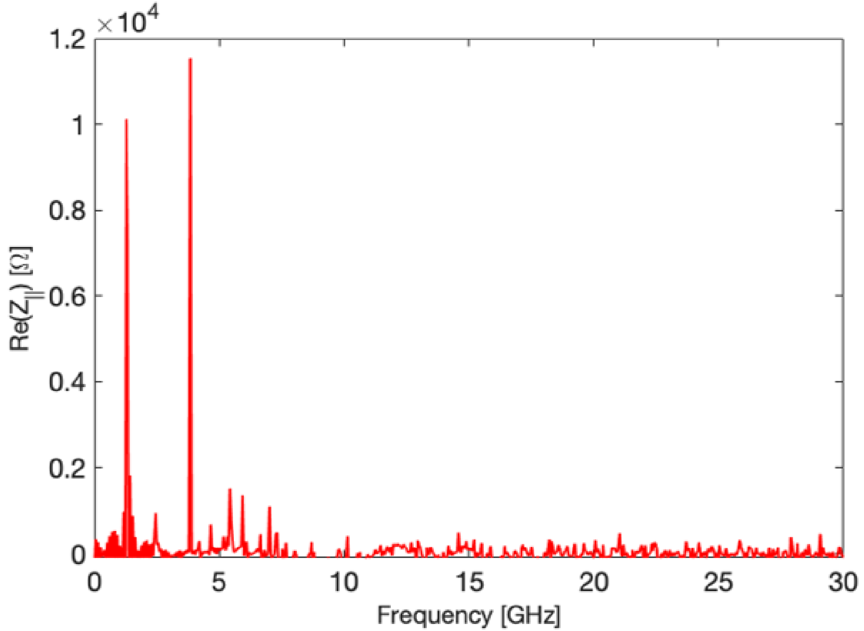
Longitudinal Impedance:

- bunch-length σ=2.2 mm
- Repetition rate ~ 100 MHz.

Main peaks relative to the longitudinal impedance :

1.3, 2.43, 3.84, 5.45 and 6.7 GHz.

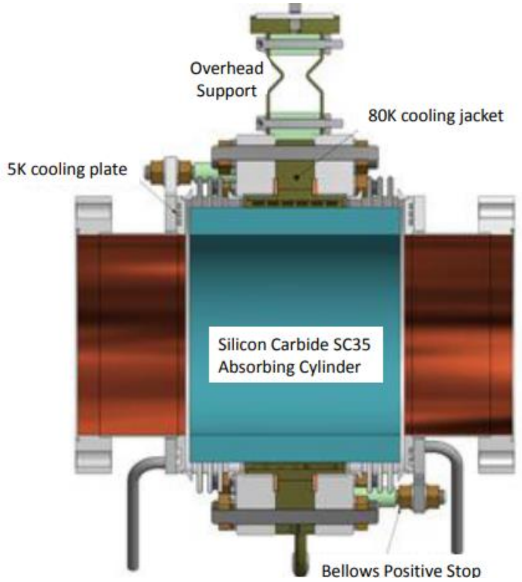




HOM Damping

In case of **high current**:

- **HOMs damping** is of the utmost importance.
- The **absorbing material** suggested for this purpose is direct graphite-sintered **Silicon Carbide SC-35** from Coorstek, which is the same used at Cornell.
- The Silicon Carbide (SiC) HOM absorber is 125mm long with hollow cylindrical shape and placed in the connecting pipes' middle.

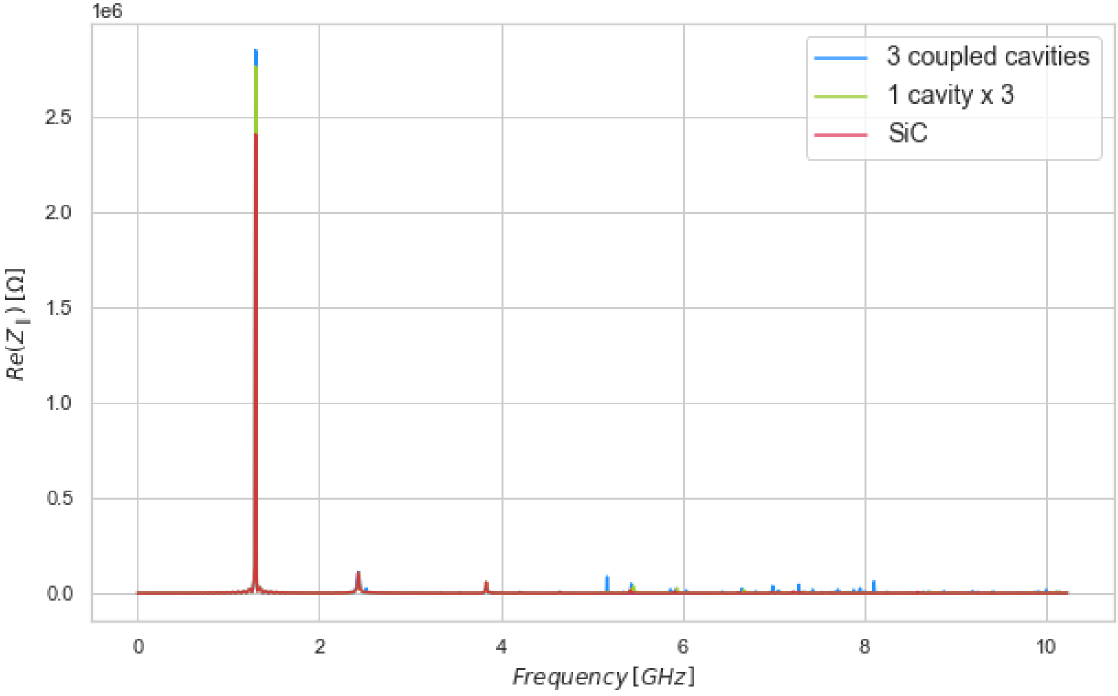


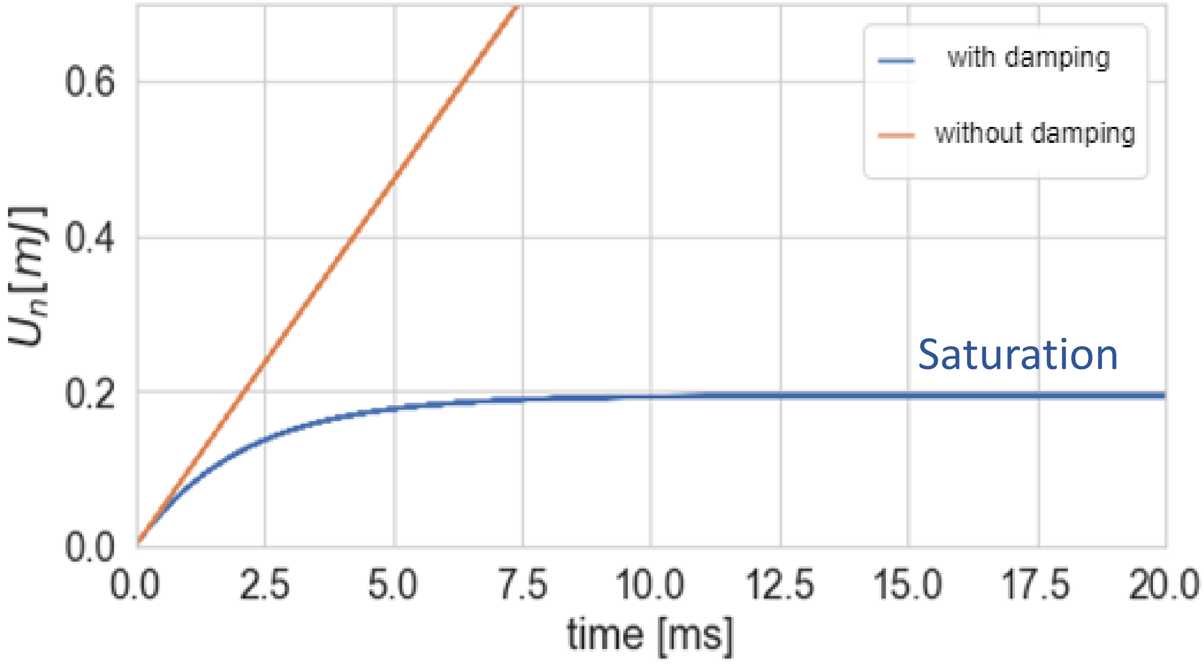
Cross section of the HOM beam line absorber

HOM beamline absorber installed on the cavity string inside the clean room (courtesy to Cornell).

HOM Damping Results

Enlarged view





Longitudinal impedance of 3 modules compared with 3 times the single module evaluation and the three modules with SiC absorber

Accelerating Mode TM010 in 7–cell SW SC cavity

HOMEN's set of equations

Based on the concept of Energy Budget

The Stored Energy variation:

$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_{L,n}} + \delta_{1,n}\left|P_{\text{kly}}\right| \pm \frac{q_i V_{acc_{n,i}}}{\tau_{cav}} + \frac{q_i^2 k_{loss,n}}{\tau_{cav}}$$

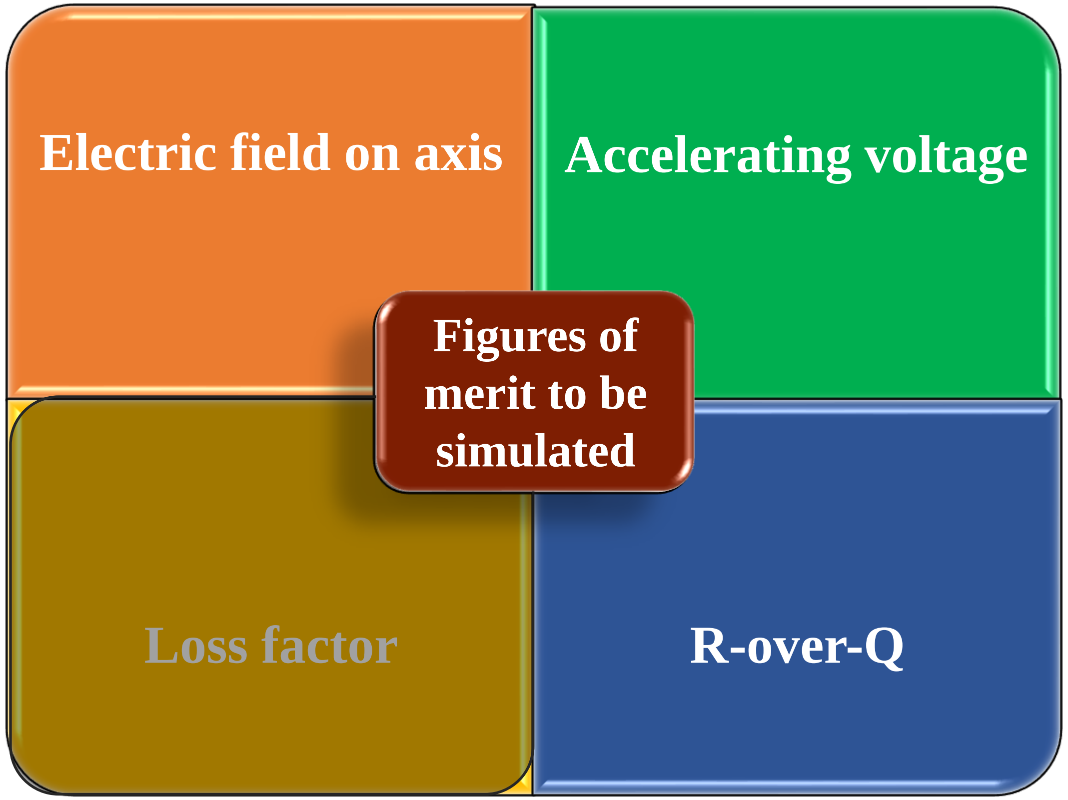
$= Q_0$

Mode Oscillation amplitude based on SVEA approximation:

$$\frac{dA_n}{dt} = \frac{A_n}{2U_n}\frac{dU_n}{dt}$$

Energy gain of the bunch:

$$\frac{d\gamma_n}{dt} = \frac{e}{m_0 c^2 \tau_{cav}} \sum_{n=1}^{N_{RF}} V_{acc_{n,i}}$$



Accelerating Mode TM010 in 7–cell SW SC cavity

HOMEN's set of equations

- Only acceleration direction have been considered

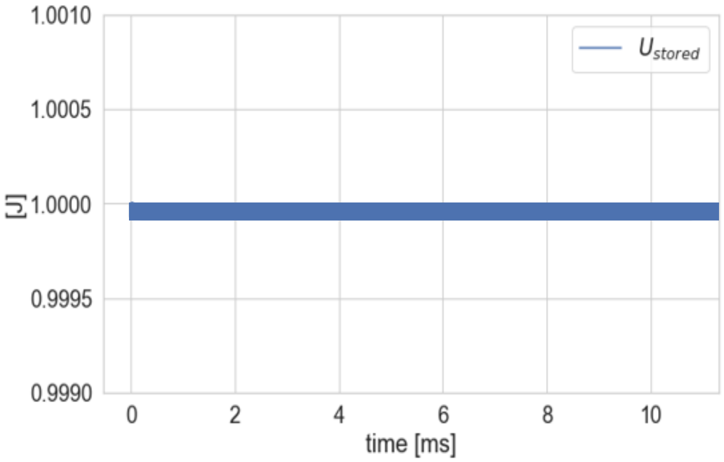
The Stored Energy variation:

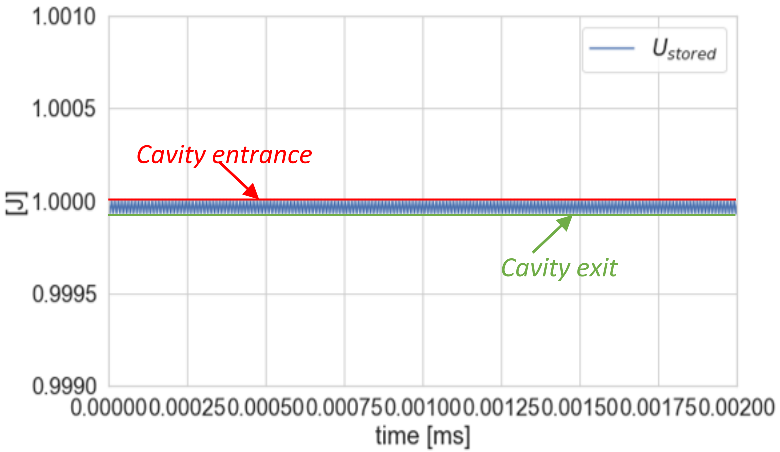
$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_0} + \delta_{1,n}\left|P_{\text{kly}}\right| \pm \frac{q_i V_{acc_{n,i}}}{\tau_{cav}}$$

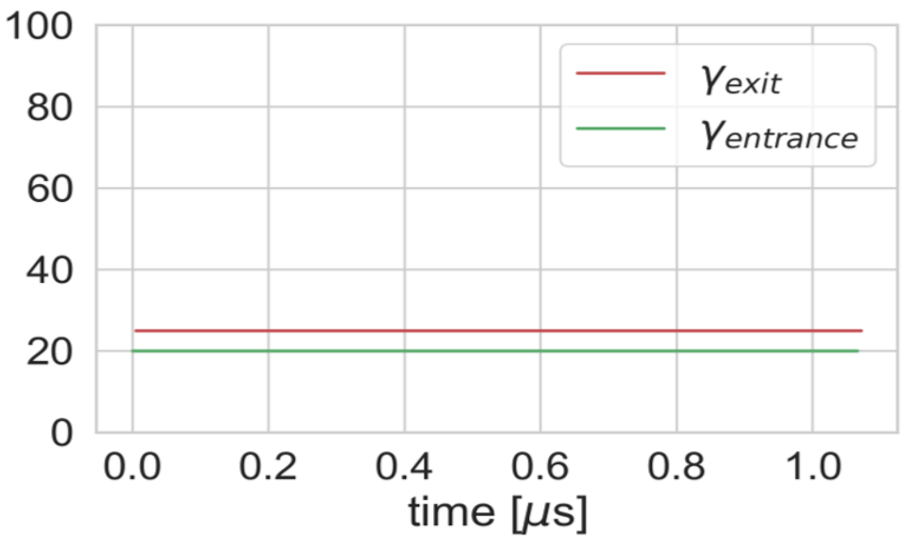
Energy gain of the bunch:

$$\frac{d\gamma_n}{dt} = \frac{e}{m_0 c^2 \tau_{cav}} \sum_{n=1}^{N_{RF}} V_{acc_{n,i}}$$

Parameters	Value
Quality factor Q_0	2.89×10^{10}
Injection energy E	10 MeV
RF frequency	1.3 GHz
Klystron Power	12.6 kW
Reptition rate	100 MHz



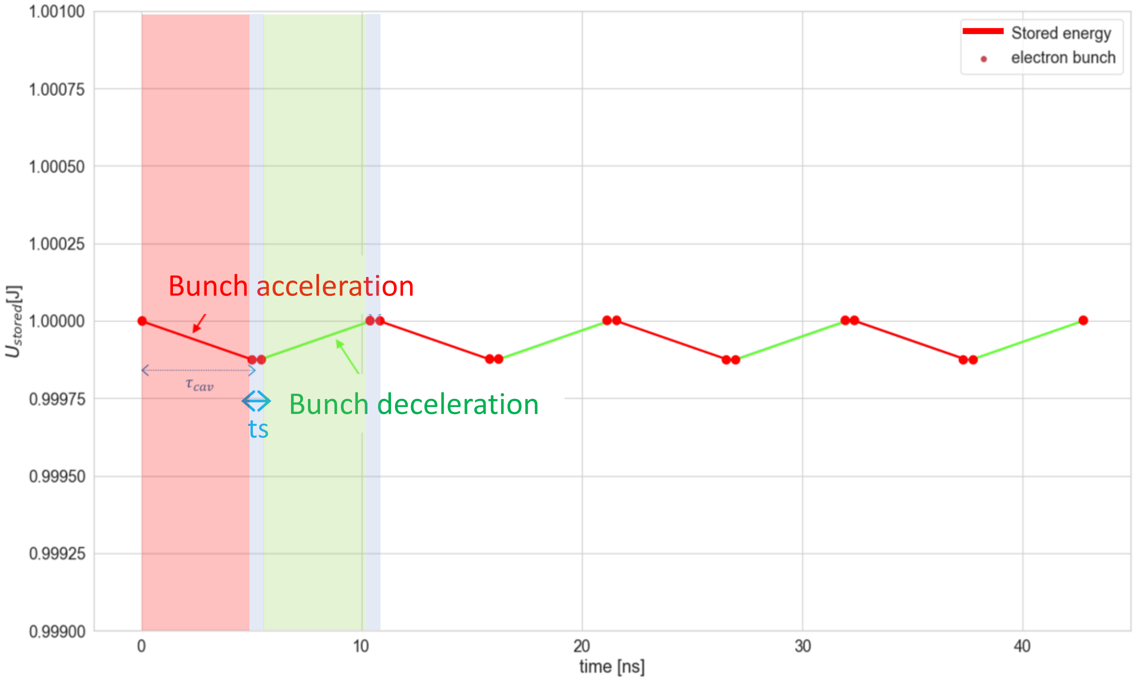




Accelerating Mode TM_{010} in ERL

ERL based on 1 module (1 SW SC cavity)

$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_{L,n}} + \delta_{1,n}\left|P_{\text{kly}}\right| \pm \frac{q_i V_{acc_{n,i}}}{\tau_{cav}}$$

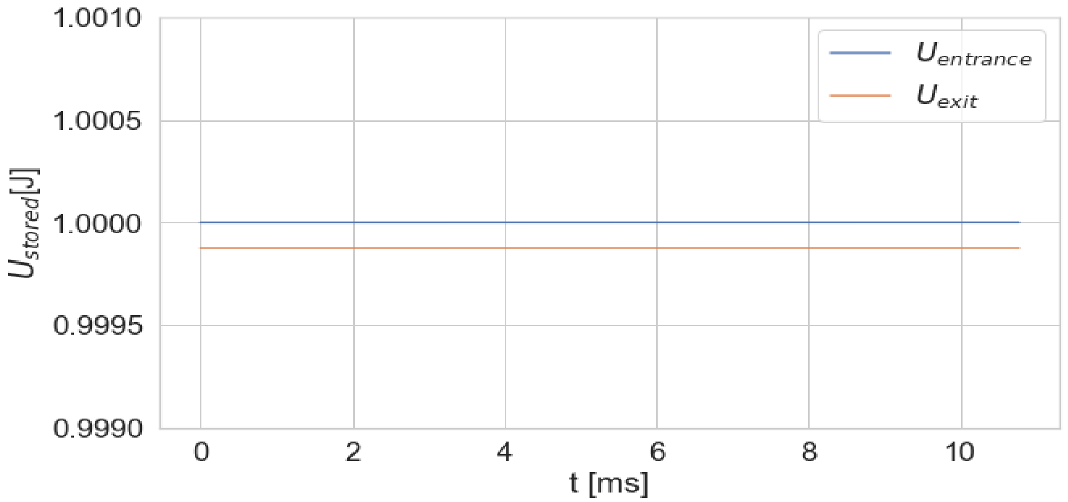


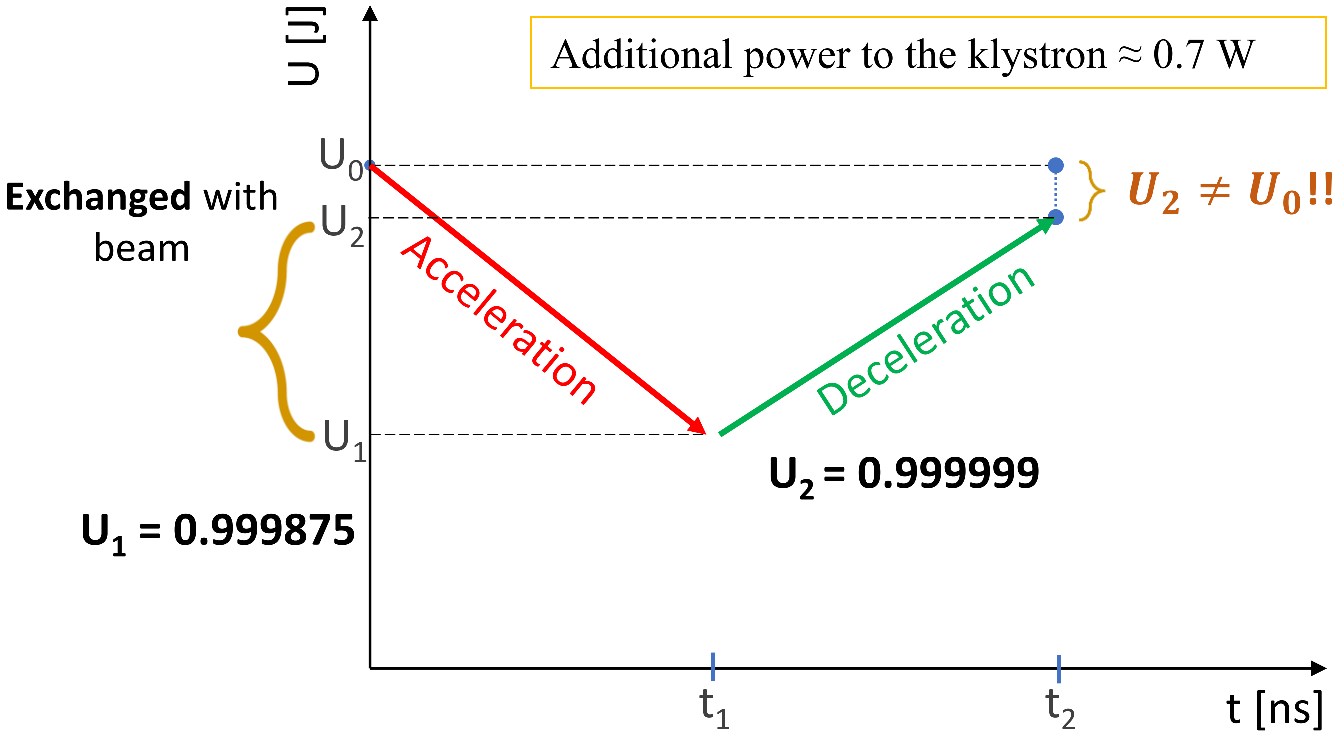
Parameters	Value
Quality factor Q_0	2.89×10^{10}
Injection energy E	10 MeV
RF frequency	1.3 GHz
Klystron Power for Linac	12.6 kW
Klystron Power for ERL	 ?

- During acceleration or deceleration we apply RK4 method (flight time τ_{cav} ≈5 ns).
- When the cavity is empty : Analytical solution with time = t_s

Energy stabilisation in the ERL cycle (Accelerating Mode TM_{010}) (1/2)

Parameters	Value
Quality factor Q_0	2.89×10^{10}
Injection energy E	10 MeV
RF frequency	1.3 GHz
One way Linac: P_{Kly}	12.6 kW
ERL: $P_{Kly} = P_{diss}$	0.28 W





Energy stored in the cavity

HOMEN's set of equations

The Stored Energy variation:

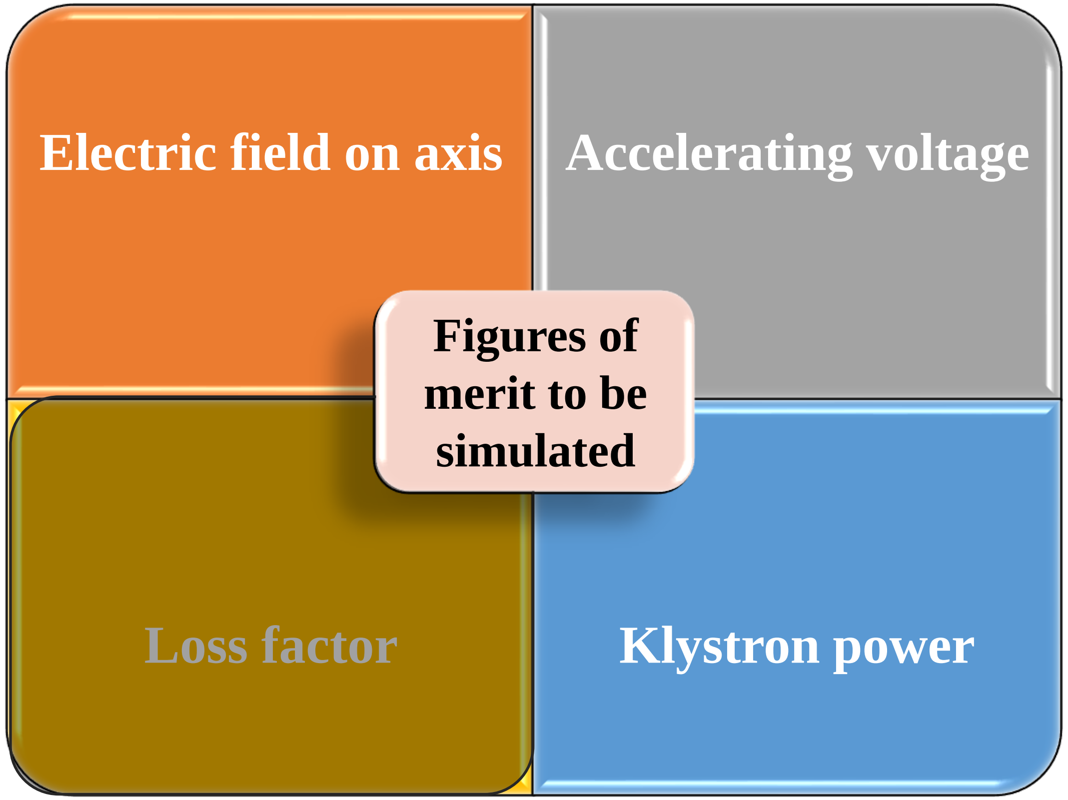
$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_{L,n}} + \delta_{1,n}\left|P_{\text{kly}}\right| \pm \frac{q_i V_{acc_{n,i}}}{\tau_{cav}} + \frac{q_i^2 k_{loss,n}}{\tau_{cav}}$$

Mode Oscillation amplitude based on SVEA approximation:

$$\frac{dA_n}{dt} = \frac{A_n}{2U_n}\frac{dU_n}{dt}$$

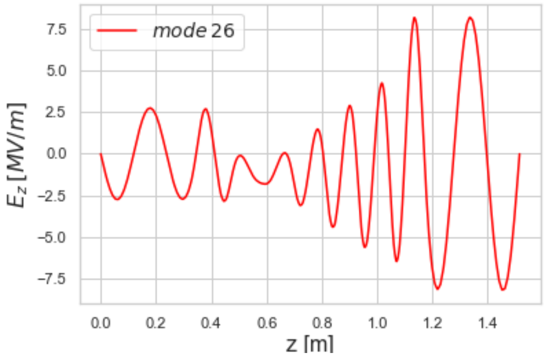
Energy gain of the bunch:

$$\frac{d\gamma_n}{dt} = \frac{e}{m_0 c^2 \tau_{cav}} \sum_{n=1}^{N_{RF}} V_{acc_{n,i}}$$



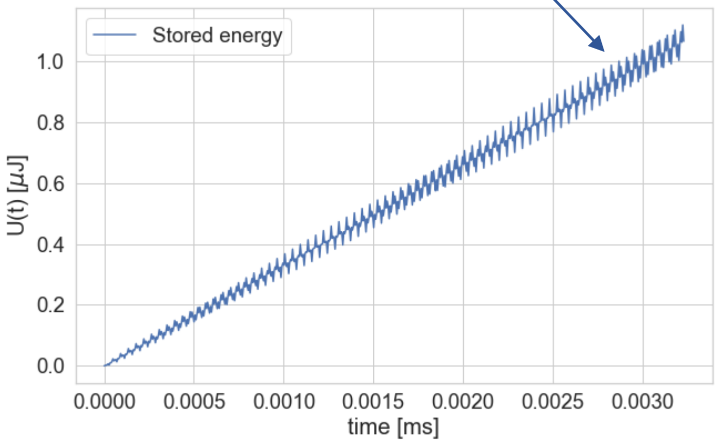
High Order modes contribution in the ERL (2/2)

Parameters	Value
Loaded Q-factor Q_L	3.147×10^7
Injection energy E	10 MeV
HOM frequency	2.43 GHz
k_{loss}	0.6 V/pC
ERL: P_{Kly}	0 W

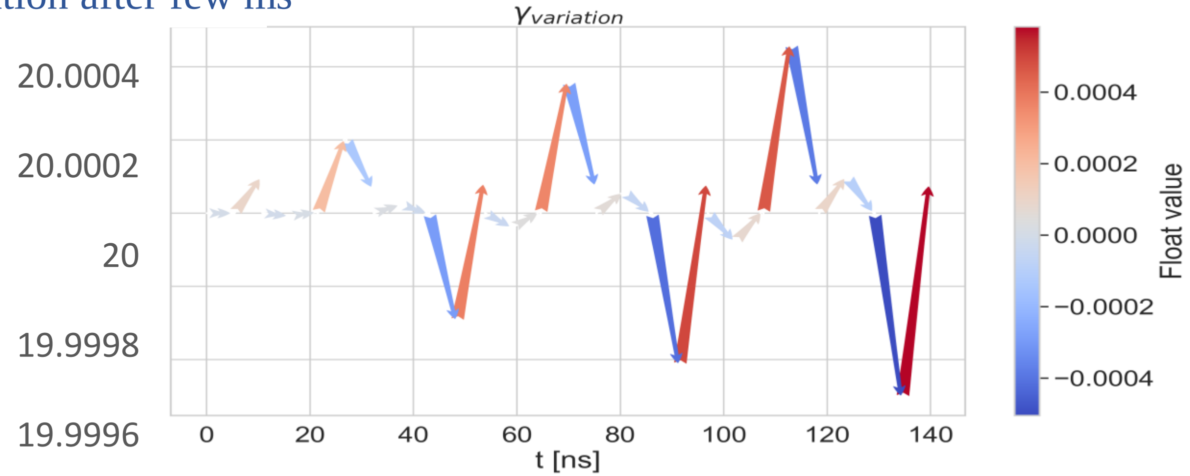


- The Electric field associated with f = 2.43 GHz
- First 300 bunches

Will get into saturation after few ms

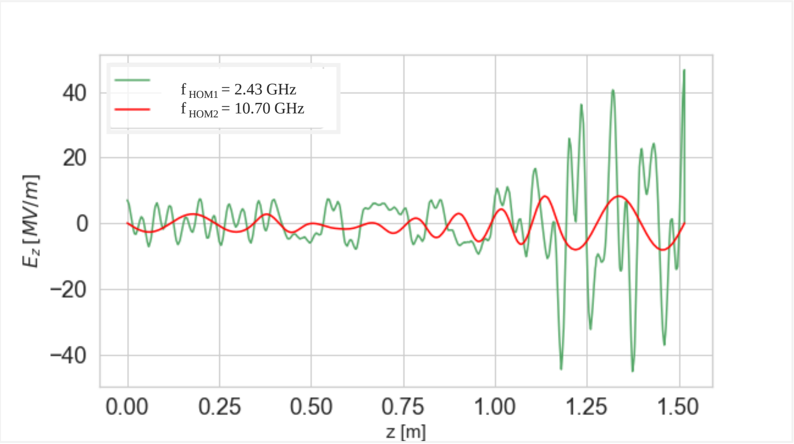


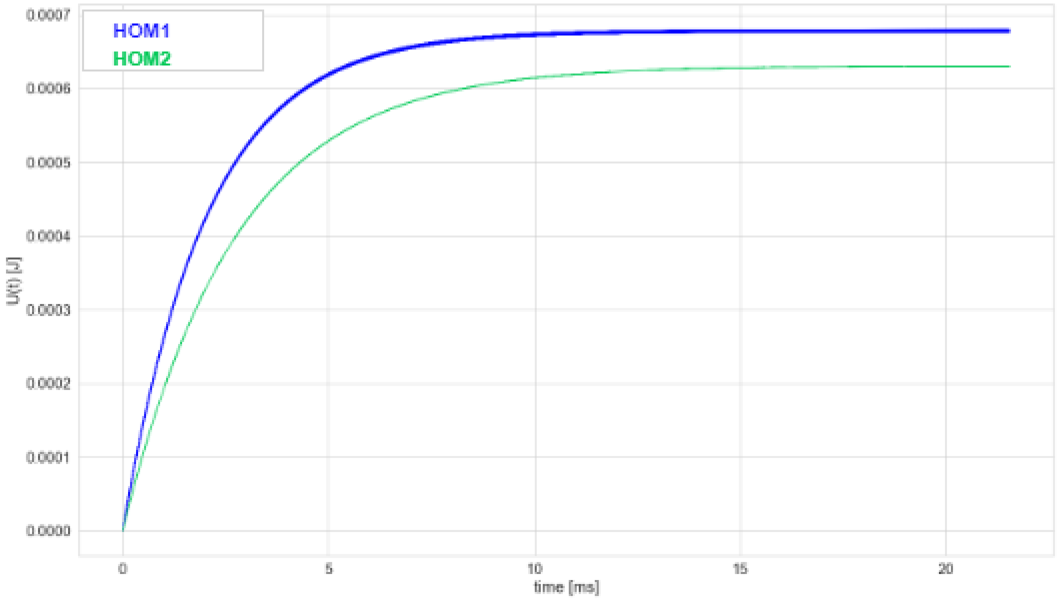
First 14 bunches

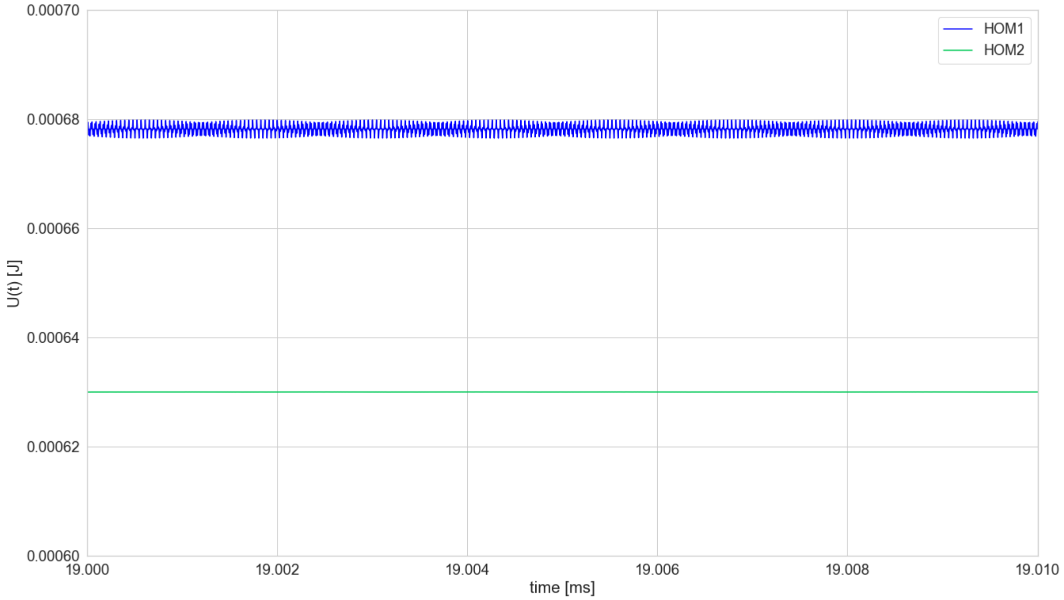


Comparative Analysis between Two HOMs in the ERL (1/2)

Parameters	Value
HOM1 frequency	2.43 GHz
HOM2 frequency	10.43 GHz
$k_{loss,\ HOM1}$	0.6 V/pC
$k_{loss,\ HOM2}$	0.2 V/pC
ERL: $P_{Kly,HOMs}$	0



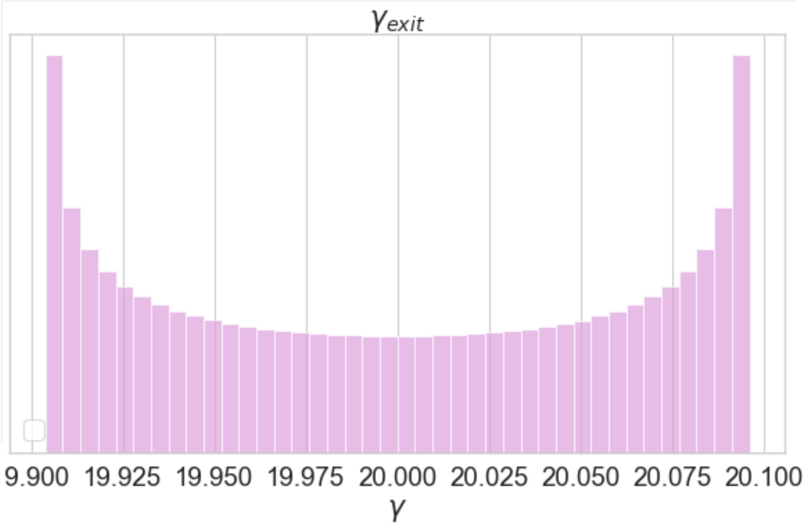




2 M bunches

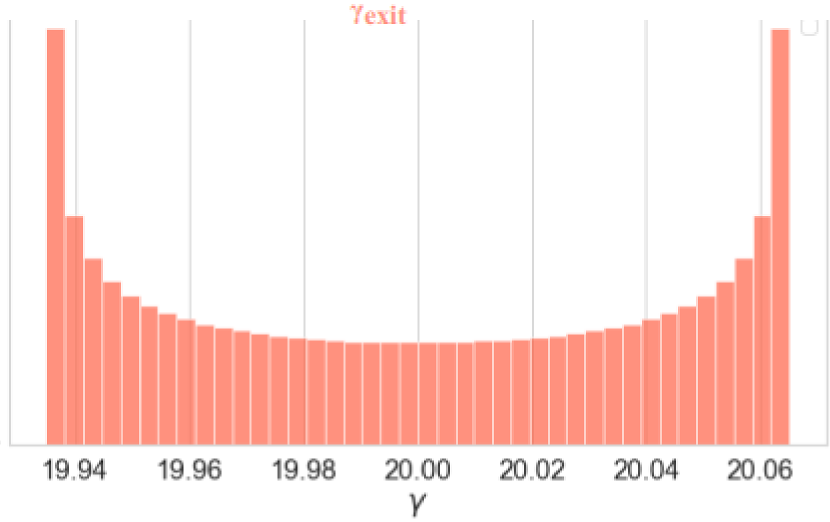
Comparative Analysis between Two HOMs in the ERL (2/2)

Parameters	Value
HOM1 frequency	2.43 GHz
HOM2 frequency	10.43 GHz
$k_{loss, HOM1}$	0.6 V/pC
$k_{loss, HOM2}$	0.2 V/pC
ERL: $P_{Kly,HOMs}$	0



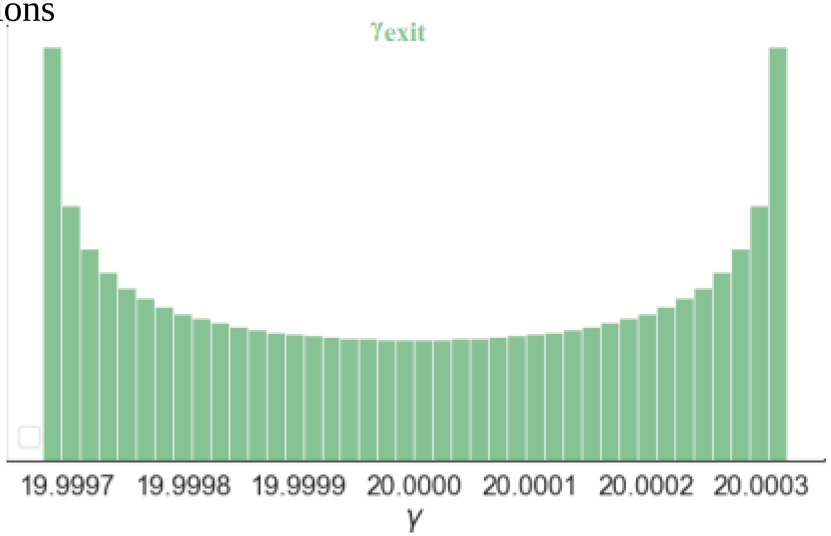
- Beam energy fluctuations about $\pm 5 \times 10^{-3}$

Bunch energy gain:



- Probability of relative Energy fluctuations of the bunch:
- k_{loss} (0.6 V/pC) => $\pm 3\times10^{-3}$
- k_{loss} (0.2 V/pC) => $\pm 1.5\times10^{-5}$

$\gamma_{exit} > \gamma_{exit}$



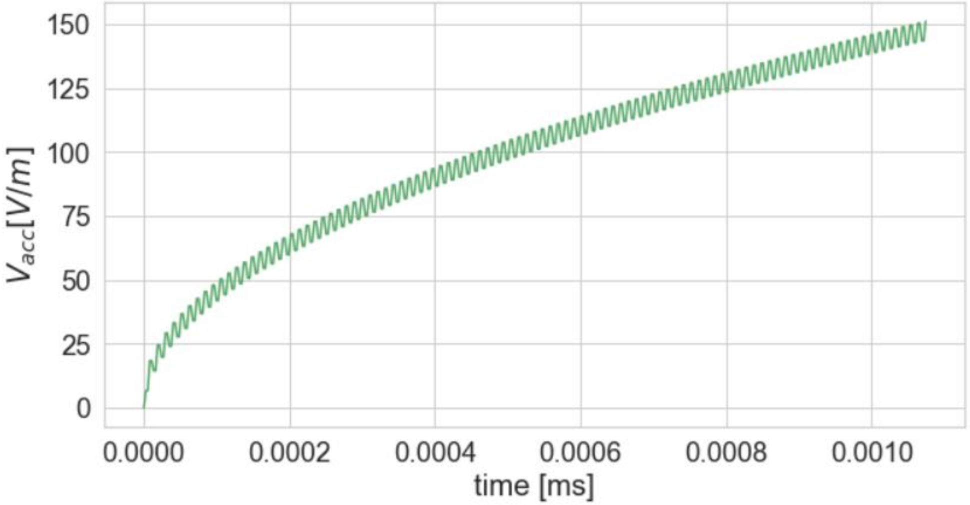
Presentation of the C-HOMEN

HOM power proportional to:

- **Bunch charge** and **beam current** → Using BriXSinO's average current
- **R/Q** (cavity shape) and quality factor **Q** for each mode

…

$$\left(\frac{R}{Q}\right)_n = \frac{V_{acc,n}^2}{\omega_n U_n}$$



$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_n} + P_{\text{kly}} - I_f \sin(\omega_r t)\sqrt{\omega_n U_n}\sqrt{\left(\frac{R}{Q}\right)_n} cos\varphi_n + |I_0\, q\, k_{loss}\,|$$

Fundamental mode Analysis (1/2)

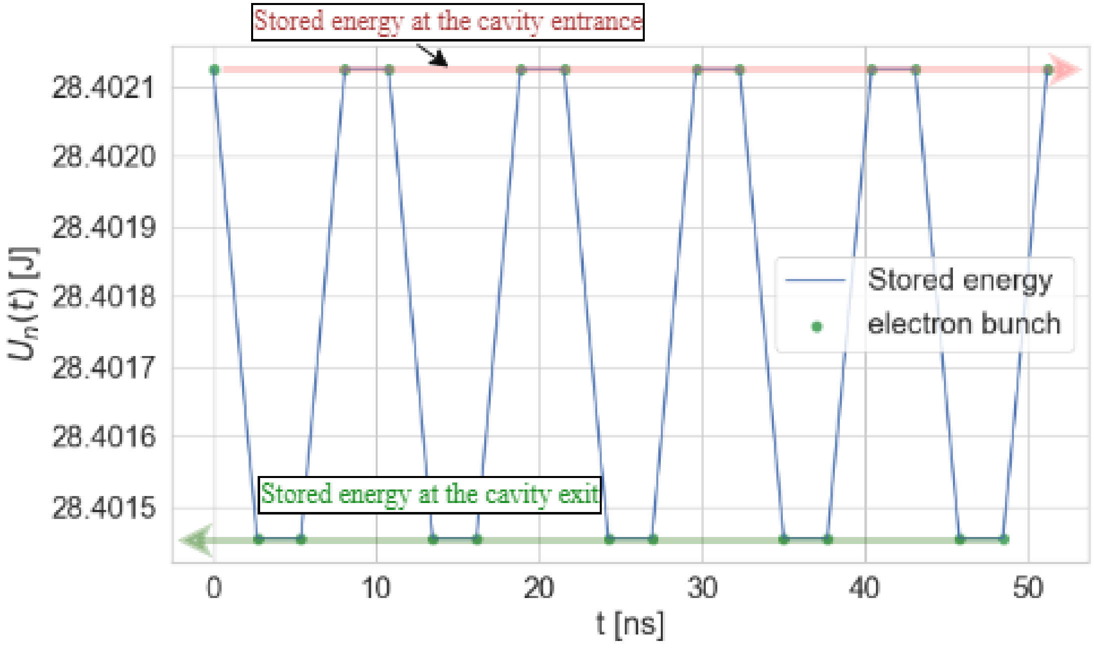
Initial energy:

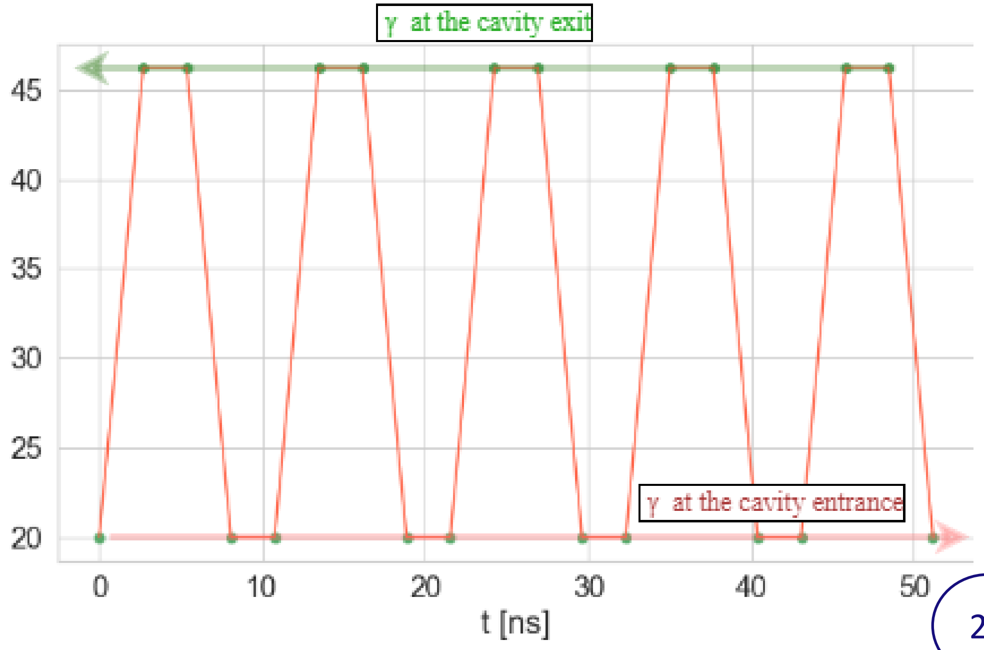
$$\frac{R}{Q} = \frac{V_{acc}^2}{\omega_n U_n} \rightarrow U_0 = \frac{V_{acc}^2}{\omega_0(\frac{R}{Q})}$$

$$where\ V_{acc} = E_{acc} \times L_{cav}$$

$$U_0 = 28.40\ J$$

Quantity	Value
Accelerating voltage V_{acc} (MV)	13.4
Accelerating gradient E_{acc} MV/m	16.5
Quality factor Q_0	2.894×10^{10}
Fundamental frequency f_0 GHz	1.3
R/Q	774





Fundamental mode Analysis (2/2)

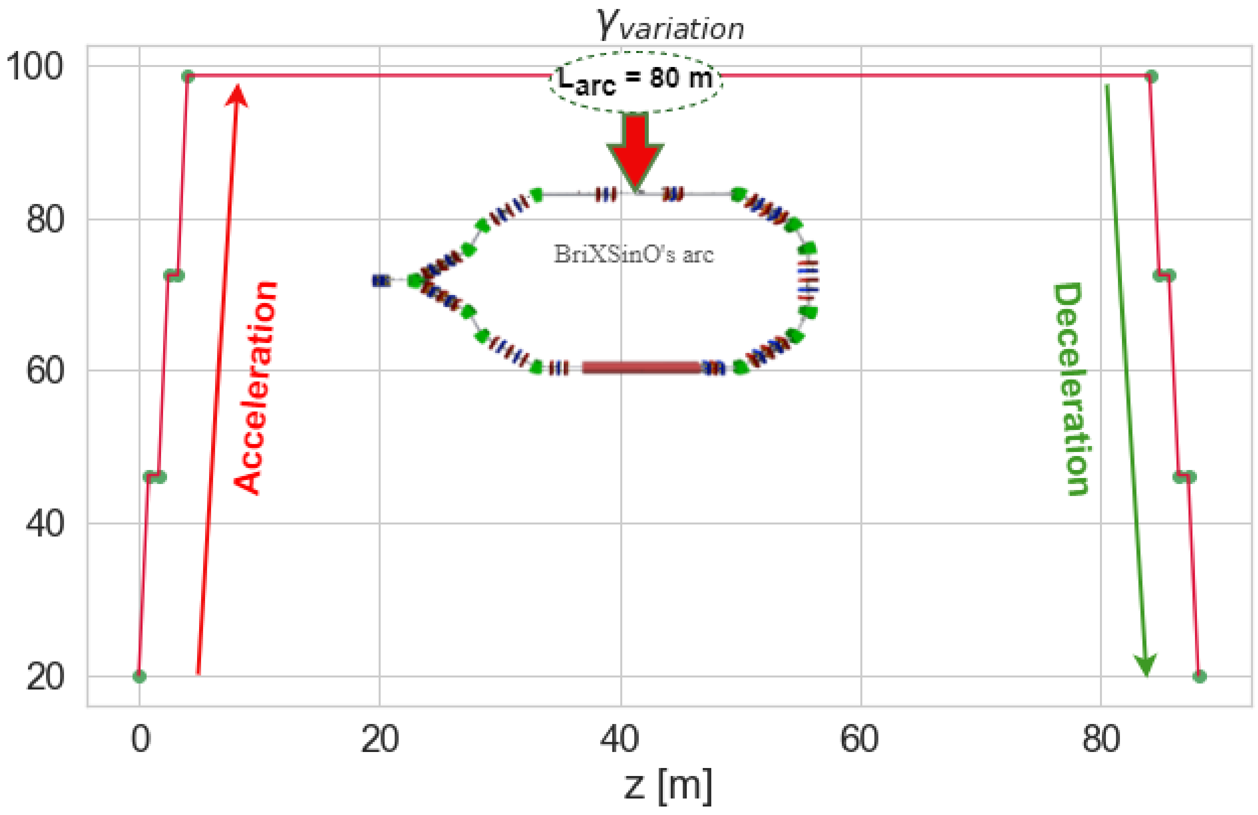
Initial energy:

$$\frac{R}{Q} = \frac{V_{acc}^2}{\omega_n U_n} \rightarrow U_0 = \frac{V_{acc}^2}{\omega_0 (\frac{R}{Q})}$$

$$where\ \ V_{acc} = E_{acc} \times L_{cav}$$

$U_0 = 28.40\ J$
$\gamma_0 = 20$

Final bunch energy gain ≈ 50 MeV
Energy recovery theoretically is 100 %

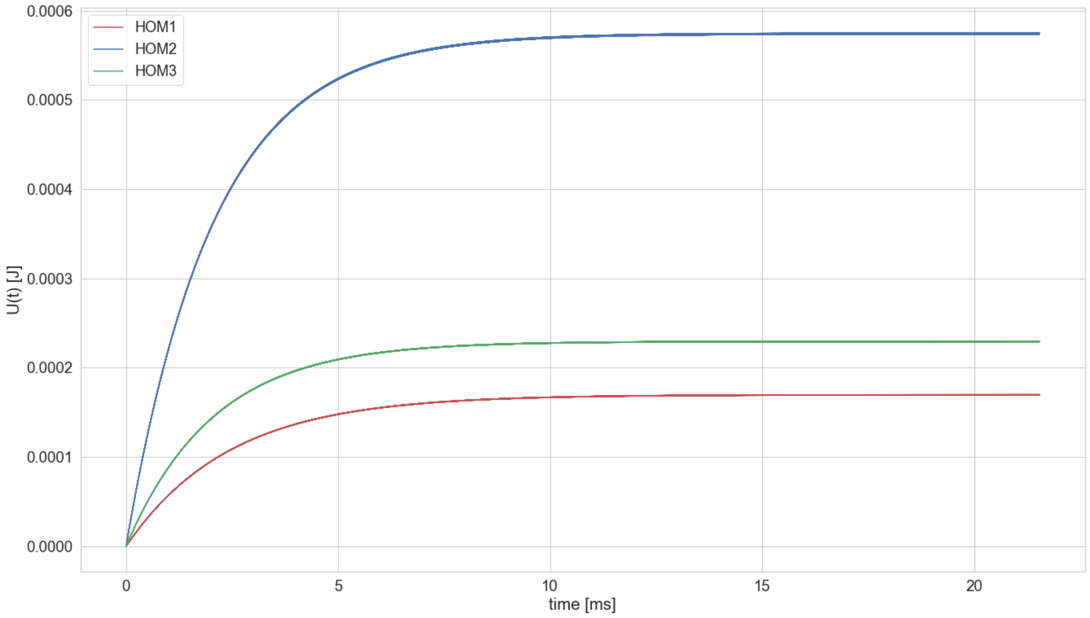


Bunch energy gain for 3 coupled cavities

HOM Analysis with the Compact HOMEN (1/2)

	Frequency (GHz)	R/Q	k_{loss} (V/pC)	Q_{loaded}	t_{ch} (ms)
HOM1 →	2.63	17.45	0.14	4.026×10^{7}	15.3
HOM2 →	2.43	108	0.6	3.147×10^{7}	12.95
HOM3 →	2.42	30.82	0.24	3.137×10^{7}	12.96

- The accumulation of energy due to the mode with the highest loss factor value (k*loss*= 0.6 V/pC) is approximately 0.6 mJ after a characteristic time of 15.3 ms.
- The storage energy buildup within the cavity leads to fluctuations in the beam energy as it exits the cavity.



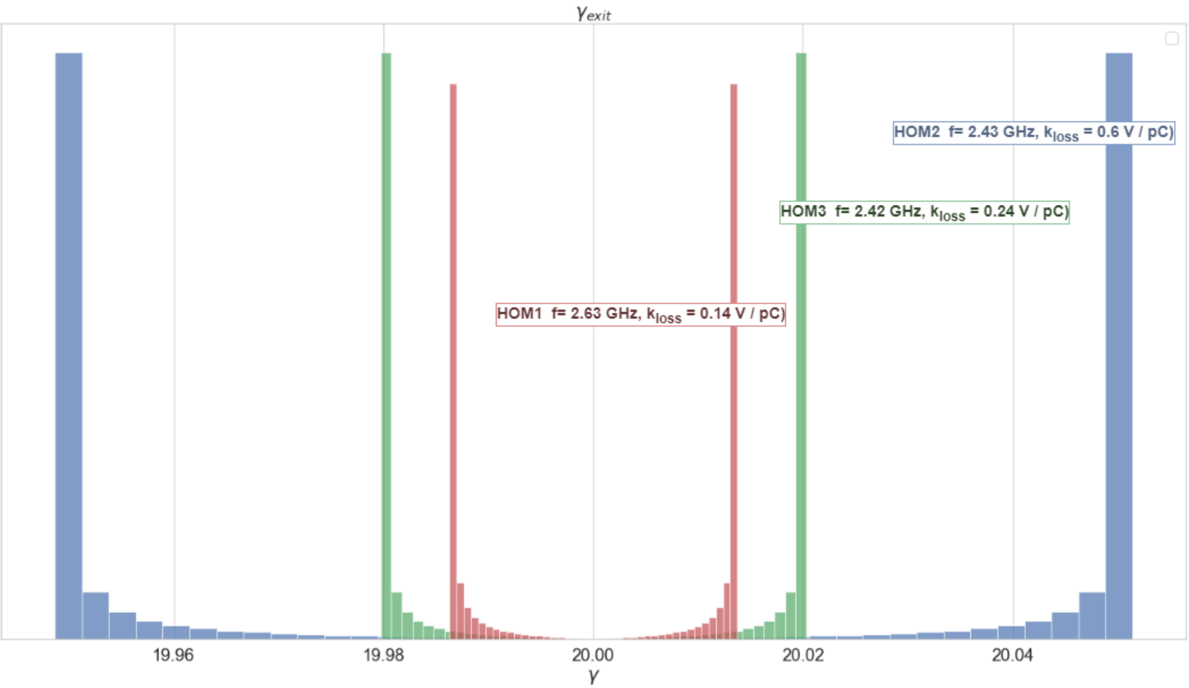
2 M bunches

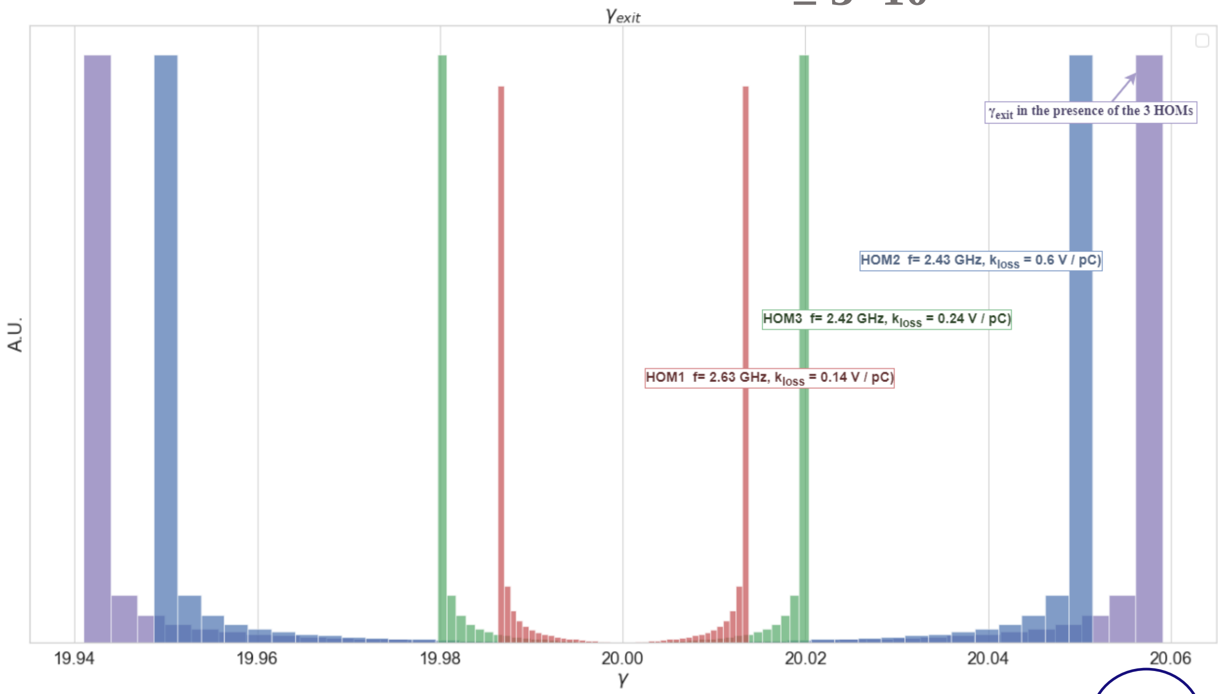
HOM Analysis with the Compact HOMEN (2/2)

Frequency (GHz)	R/Q	k_{loss} (V/pC)	Q_{loaded}	t_{ch} (ms)
2.63	17.45	0.14	4.026×10^{7}	15.3
2.43	108	0.6	3.147×10^{7}	12.95
2.42	30.82	0.24	3.137×10^{7}	12.96

Beam fluctuations $\pm 2.5\times10^{-3}$

$\pm 3\times10^{-3}$





Conclusion

Outlook:

- BriXSinO project is still in progress.
- Include more theoretical physics into HOMEN like Transverse beam dynamics and more theoretical studies in HOMEN and C-HOMEN.

✓ **The models** are able to study the effects of **HOMs** on **beam quality and stability** in SC cavities back and forth in CW operation.

✓ Assessing the **beam's performance** in an ERL at **high average current** levels and ensuring it meets the required **beam quality** for **FEL** is of significant importance.

✓ Energy recovery based on a theoretical and numerical model has been achieved and approved for TPTW.

✓ This activity will be very useful in the context of BriXSinO project which is under development at LASA laboratory in Milan.

Beam Breakup and High Order Modes Instabilities Studies for Energy Recovery Linear Accelerators

Sanae SAMSAM | PhD School: FISICA DEGLI ACCELERATORI

Thank you

SAPIENZA UNIVERSITÀ DI ROMA

INFN MILANO
Istituto Nazionale di Fisica Nucleare
Sezione di Milano

Supervisor:
Luca Serafini