PERLE buncher design update

(IJCLab, Orsay, 30 Jan 2025)

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30.January.2025

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  - Review of activities
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    - RF model
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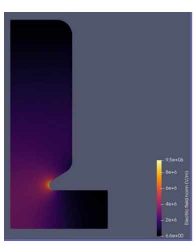
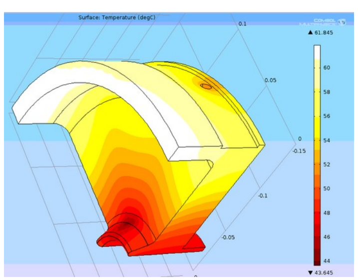
    - Thermomechanical deformation detuning
    - Electric field asymmetry effect on beam dynamics
    - ...
  - Collaboration issues
  - Coupler / tuner conceptual design

Design activities - 1

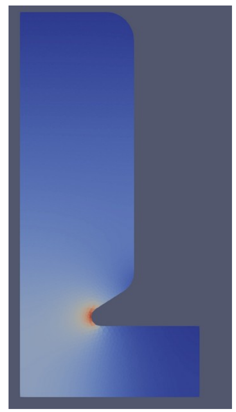
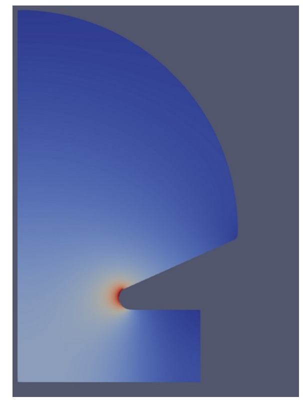
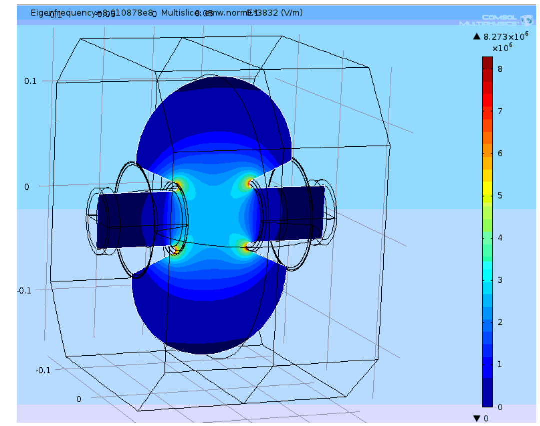
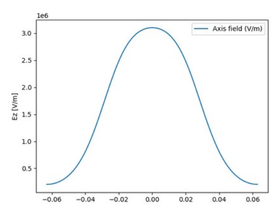
- 801.56 MHz
- Gradient: 1.4 MV/m
- Aperture: 50 mm
- S11 < -20 dB
- K = 350 keV
- CW
- Iris coupling

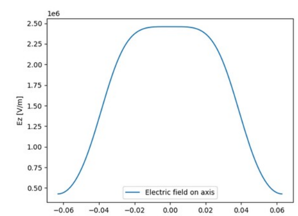
Initial specs.
Apr. 2023

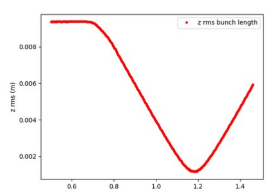
PERLE Meeting, CERN June 2023 preliminary design
- Nosecone:

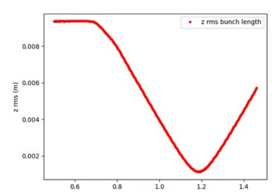



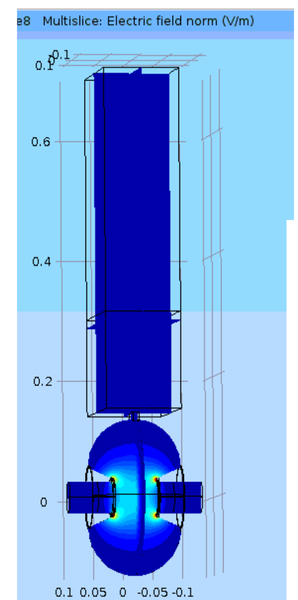
PERLE meeting
16.January.2024

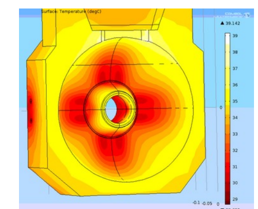
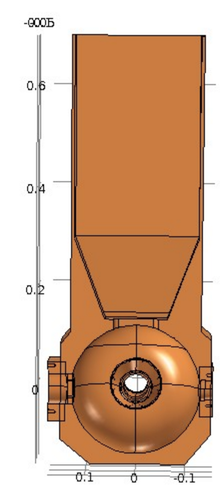













- Nosecone
- 2.5D/3D design
- Iris -22 dB
- Q0 = 22000
- P=8400 W

- cERL type
- 2.5D/3D design
- Iris -38 dB
- Q0 = 25200
- P=5000 W

Design activities - 2

June 2024, contribution to CDR

Technical Design Report for PERLE Buncher

J.L. Muñoz, ESS-Bilbao, 24-June-2024

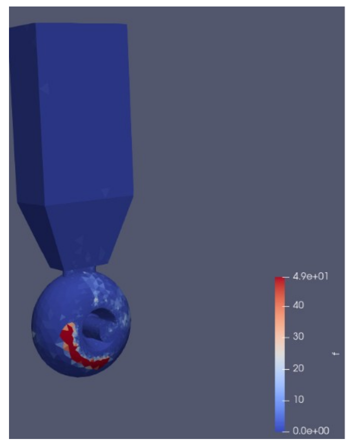
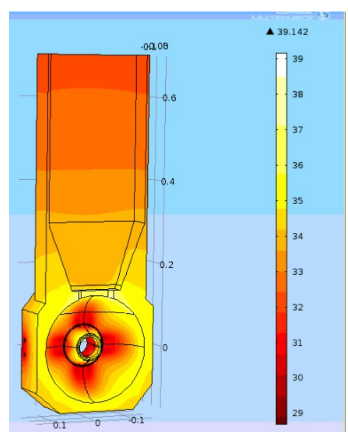
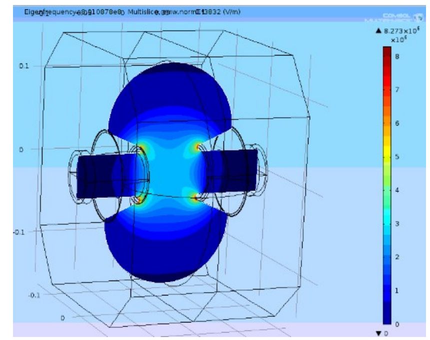
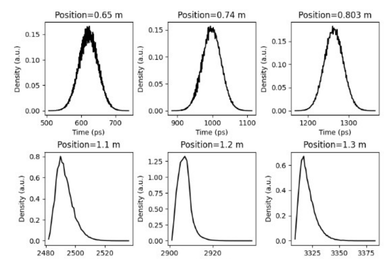
1. Introduction

A critical component in the PERLE injector is the buncher cavity. The electron beam that emerges from the electron gun elongates due to space charge, and it needs to be compressed from a length of about 10 mm to a length of 3 mm. This report summarizes the design and optimization of the PERLE injector buncher cavity presented in [1], providing insights into its specifications, simulation results, and engineering considerations.

The figures of merit of the proposed buncher design are collected in Table 1.

Parameter	Specification	2D-model	3D-model, coupler. Pin=5 kW
Beam pipe diameter (m)	0.050	0.050	0.050
Frequency (MHz)	801.603	801.6	797.0 (with waveguide, no tuner)
Gradient (MV/m)	1.4	1.4	1.392
Electron energy (beta)	350 keV (0.8048)		
Half cavity length (m)		0.063	0.063
V0 (MV)		0.21	0.209
V0T (V)		176400	174154
ZTT (MOhm/m)		49.7	49.7
TTF		0.840	0.840
Power loss (W)		4968	4972
Q0		25268	21522
Max. surface field (MV/m)		7.25	11.8
S11dB	< -20 dB		-35.81 dB
Wave guide			WR-975 (274.65 x 123.80 mm)
Iris racetrack shape a,b (m)			0.070 x 0.020 m

PERLE meeting CERN 16-17.September.2024 - EM optimization design nosecone / cERL

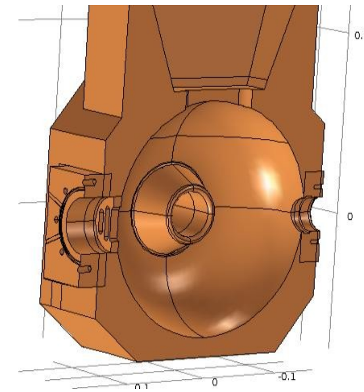
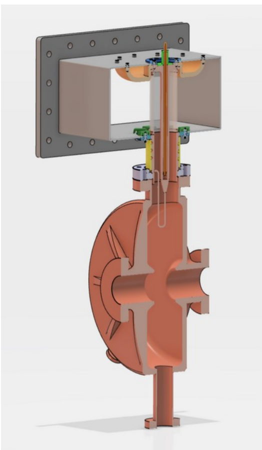


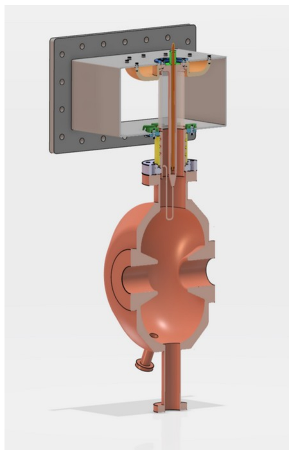
Figure of merit	PERLE buncher cERL-like optimized	Figure of merit	PERLE buncher cERL-like optimized
Input power	5 kW	Iris a	0.070 m
V0	0.21 MV	Iris b	0.020 m
TTF	0.84	Wave guide	WR-975 (274.65 mm, 123.80 mm). Taper=0.5
Gradient (V_0T/L_{cav})	1.392 MV/m	S11dB	-35.81 dB
Power loss	4972 W	ZTT	49.7 MΩ/m
RsTT = $(V0T)^2$ / Ploss	6.26 MΩ	Esurf_max	8.21 MV/m

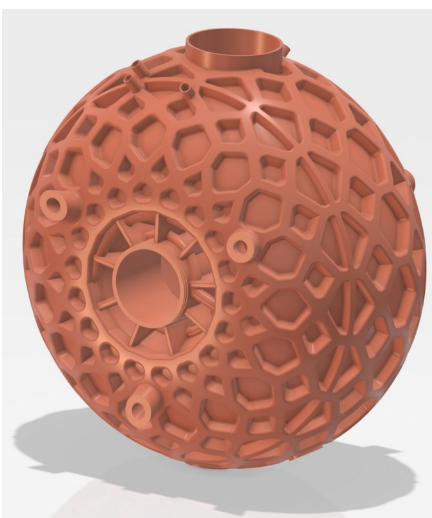
Parameter	Specification	2D-model	3D, P_{in}=5 kW
Beam pipe diameter (m)	0.050	0.050	0.050
Frequency (MHz)	801.603	801.6	797.0 (no tuner)
Gradient (MV/m)	1.4	1.4	1.392
Electron energy (beta)	350 keV (0.8048)		
Half cavity length (m)	0.063	0.063	0.063
V0 (MV)	0.21	0.21	0.209
V0T (V)	176400	176400	174154
ZTT (MOhm/m)	49.7	49.7	49.7
TTF	0.840	0.840	0.840
Power loss (W)	4968	4968	4972
Q0	25268	25268	21522
$E_{surf,max}$ (MV/m)	7.25		11.8
S11dB	<-20 dB		-35.81 dB
Wave guide	WR-975 (274.65 x 123.80 mm)		
Iris racetrack a,b (m)			0.070 x 0.020 m

Table 4: Parameter comparison between specification, 2D-model, and 3D-model.

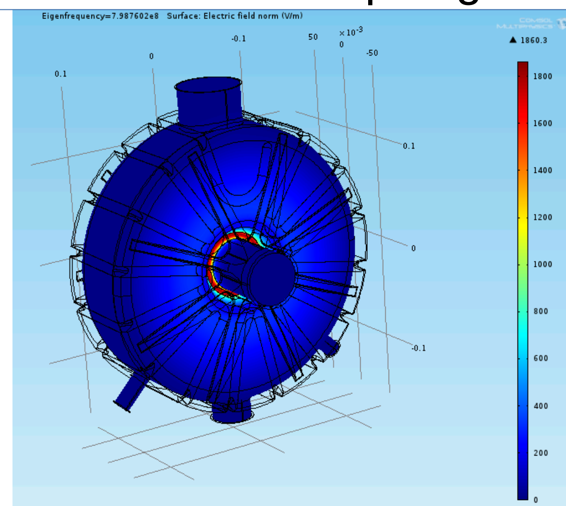
Design activities - 3

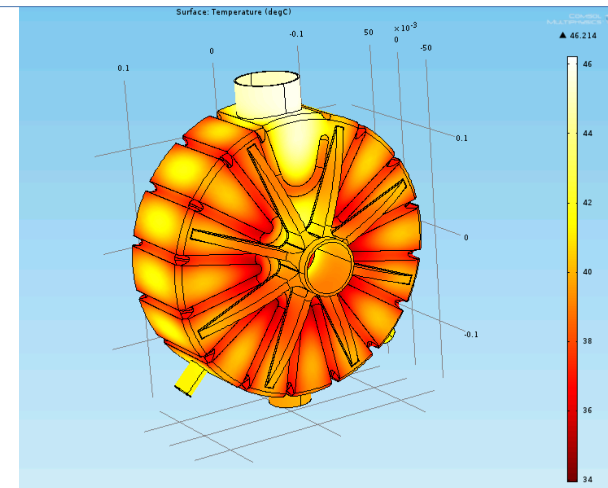


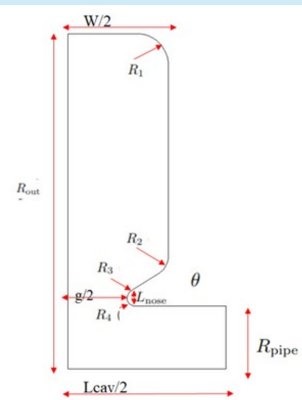


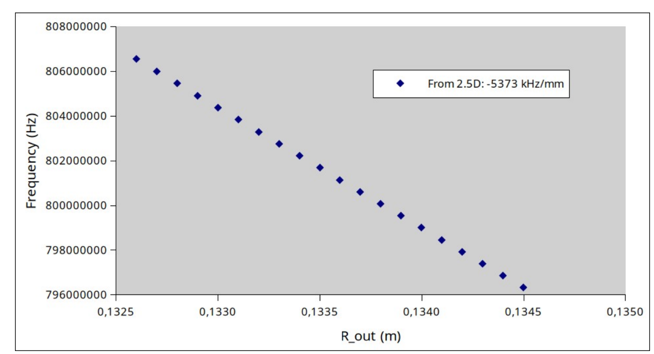


Online meeting 16.December.2024
Several decisions:
- Nose-cone design
- Preference of loop coupler
- Preference of plunger tuner







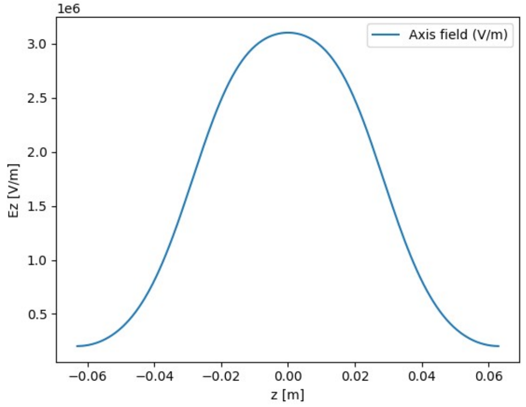


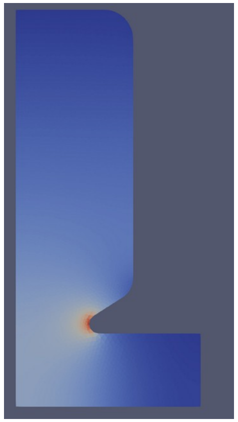
Electromagnetic design

- Focusing on nose-cone buncher design

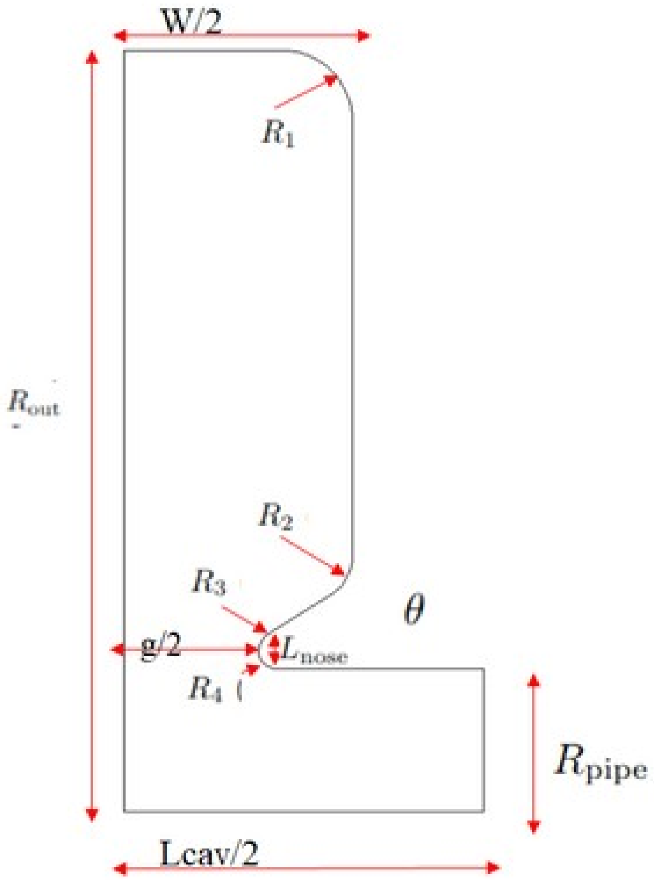
Beam pipe diameter	50 mm
Electrons K (beta)	350 keV (0.8048)
RF frequency	801.56 MHz
Duty cycle	CW
Cavity gradient	1.4 MV/m
Beam intensity	20 mA
$S_{11}dB$	< -20 dB
Emittance ε_{xy}	3.9 mm mrad
σ_{xy}	3.2e-3
Twiss beta	$\sigma_{xy} * \sigma_{xy}/\varepsilon_{xy}$
Initial bunch length	9.2 mm (rms)
Initial energy spread	0.44 %

Table 1: Specifications provided as input for the design





- Parametric 2.5D geometry



Electromagnetic design

- Electromagnetic FEM calculations
  - Python-driven scripting
  - Geometry + meshing: gmsh
  - Solving EM using ELCANO (FeniCSx + SLEPc based)
  - Optimization using MVA, genetic, ...
  - Optimization target: maximize effective shunt impedance (minimize power losses)

$$V_0 = \int_{-L_{cav}/2}^{L_{cav}/2} E_z(z)dz \qquad (1)$$

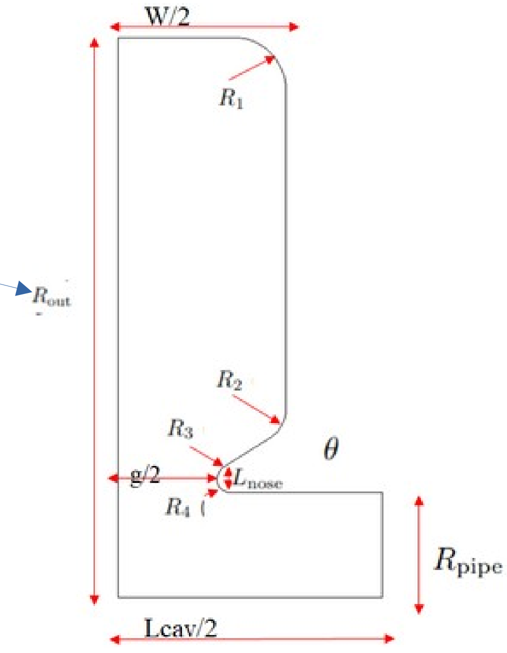
$$V_0T = \int_{-L_{cav}/2}^{L_{cav}/2} E_z(z)\cos\omega t\, dz = \int_{-L_{cav}/2}^{L_{cav}/2} E_z(z)\cos\frac{\omega z}{\beta c}\, dz \qquad (2)$$

$$gradient = V_0T/L_{cav} = 1.4\, MV/m \qquad (3)$$

$$RsTT = (V0T)^2/P_{loss} \qquad (4)$$

$$ZTT = RsTT/L_{cav} \qquad (5)$$

Free parameter to match frequency

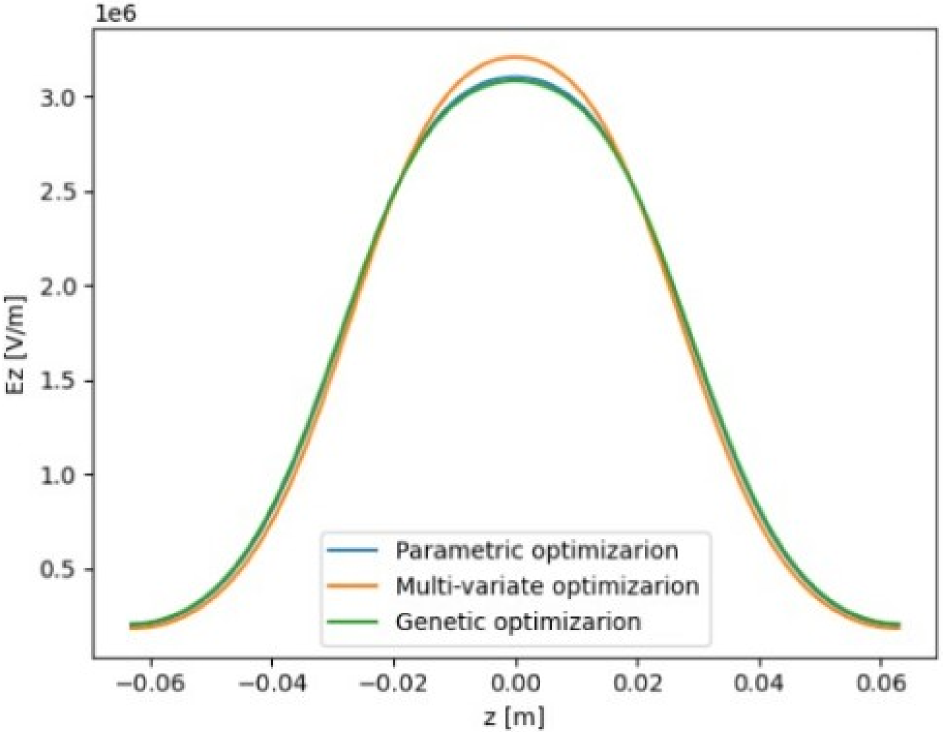


Electromagnetic design

- Different optimization methods

	Parametric	MV minimization	Genetic
Parameters			
$R_{pipe}[m]$	0.025	0.025	0.025
$g[m]$	0.05	0.0472	0.0511
theta [deg]	32.5	32.57	32.93
$R1[m]$	0.01	0.0125	0.0122
$R2[m]$	0.075	0.0081	0.00459
$R3[m]$	0.0032	0.025	0.025
$R4[m]$	0.0032	0.0032	0.0032
$W[m]$	0.08	0.08	0.08
$R_{out}[m]$	0.1352	0.1336	0.1354
$L_{nose}[m]$	0.005	0.005	0.005
$L_{cav}[m]$	0.126	0.126	0.126
Figures of merit			
Frequency [MHz]	801.048	801.603	801.759
$V_0\,(V)$	199316	198231	199657
$V_0 T\,[V]$	176400	176400	176400
Calc. gradient [MV/m]	1.4	1.4	1.4
Power loss [W]	8483	8399	8499
Q_0	22043	22013	22163
ZTT	29110994	29404319	29057634
E_{max}/E_{kilp}	0.3667	0.377	0.278

Table 2: Parameters and and figures of merit for the three optimization method (nose-cone design).

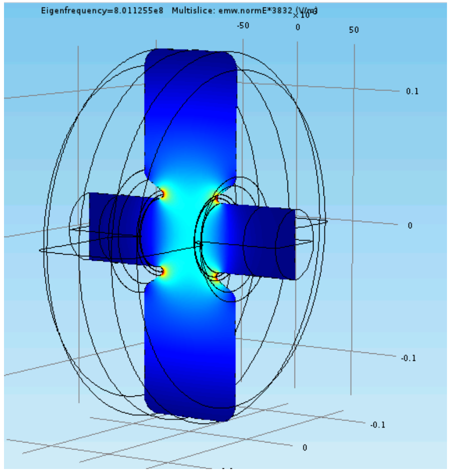


Electromagnetic design

- Selected solution:

Table 6: Design Parameters PERLE buncher Nose_Cone_1

Parameter	Value
R_{pipe} (m)	0.025
g (m)	0.0472
θ (deg)	32.57
R_1 (m)	0.0125
R_2 (m)	0.0081
R_3 (m)	0.0032
R_4 (m)	0.0032
W (m)	0.08
R_{out} (m)	0.1336
L_{nose} (m)	0.005
L_{cav} (m)	0.126
lc_1 (m)	0.0002
lc_2 (m)	0.0002
β	0.8048
RF frequency (Hz)	8.0156×10^8
Conductivity σ (S/m)	5.8×10^7
Gradient (V/m)	1.4×10^6
Geometry filename	`perle_buncher_nosecone_01_geom.dxf`



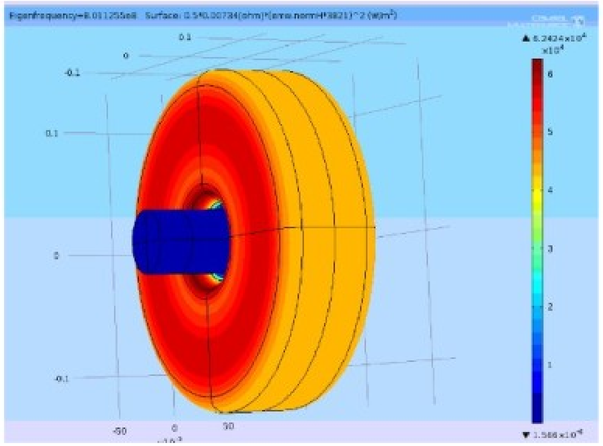
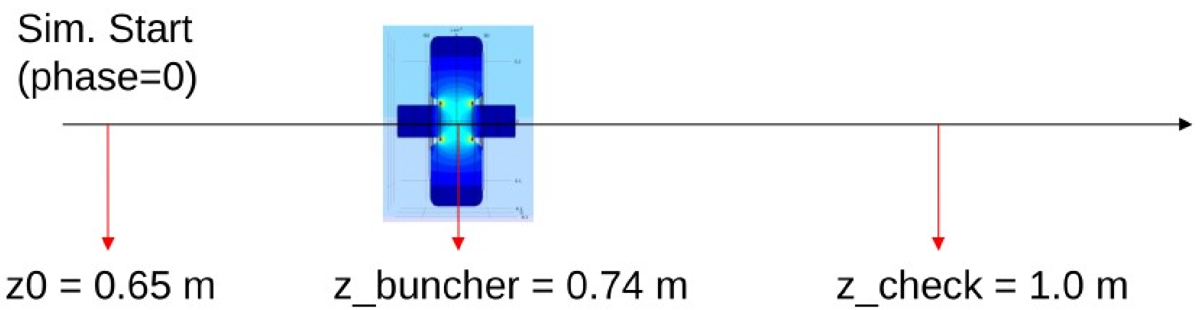
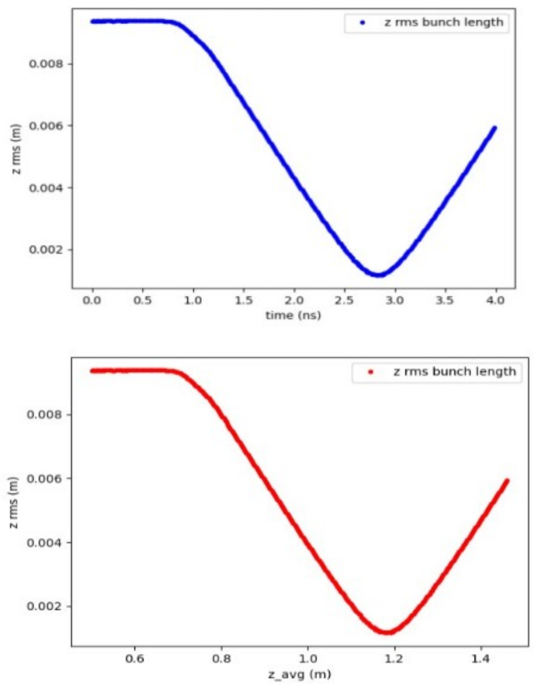


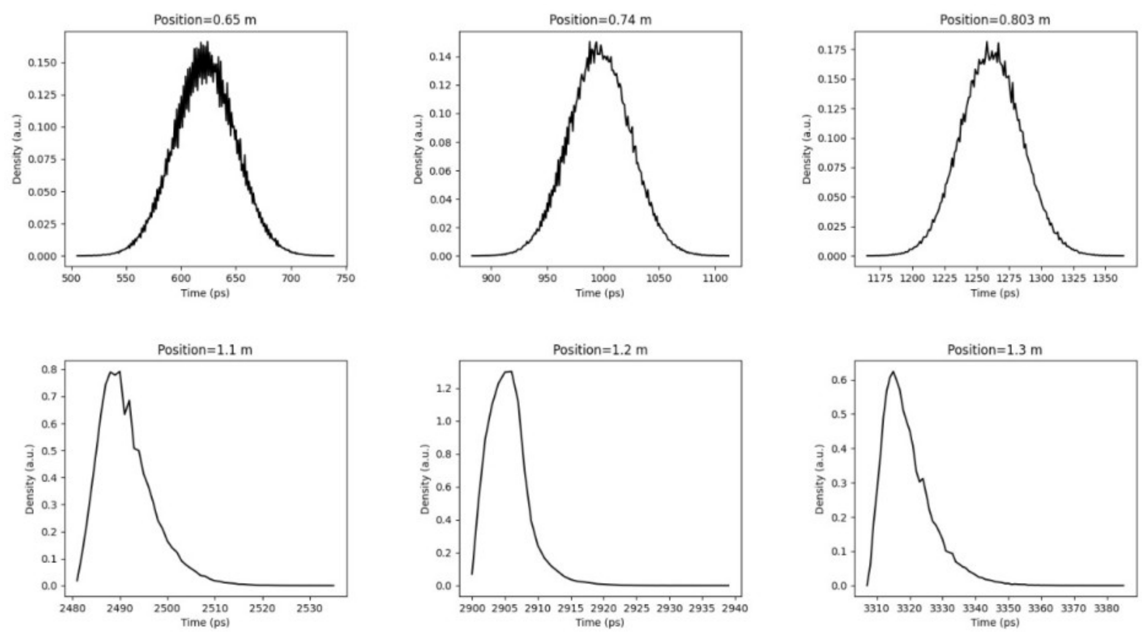
Figure of merit	ELCANO 2.5D (337 ktri)	COMSOL 3D (434 ktets)
Gradient (V_0T/L_{cav})	1.4 MV/m	1.4 MV/m
RF frequency	801.127 MHz	801.125 MHz
TTF	0.89	0.89
Power loss	8396 W	8419 W
Q0	22004	22145
RsTT = $(V0T)^2$ / Ploss	3.706 MΩ	3.696 MΩ
ZTT	29.4 MΩ/m	29.3 MΩ/m
Esurf_max	8.78 MV/m	9.35 MV/m
Ez_max	3.2 MV/m	3.2 MV/m

Electromagnetic design

- Beam dynamics verification (GPT simulations with exported electric field map):

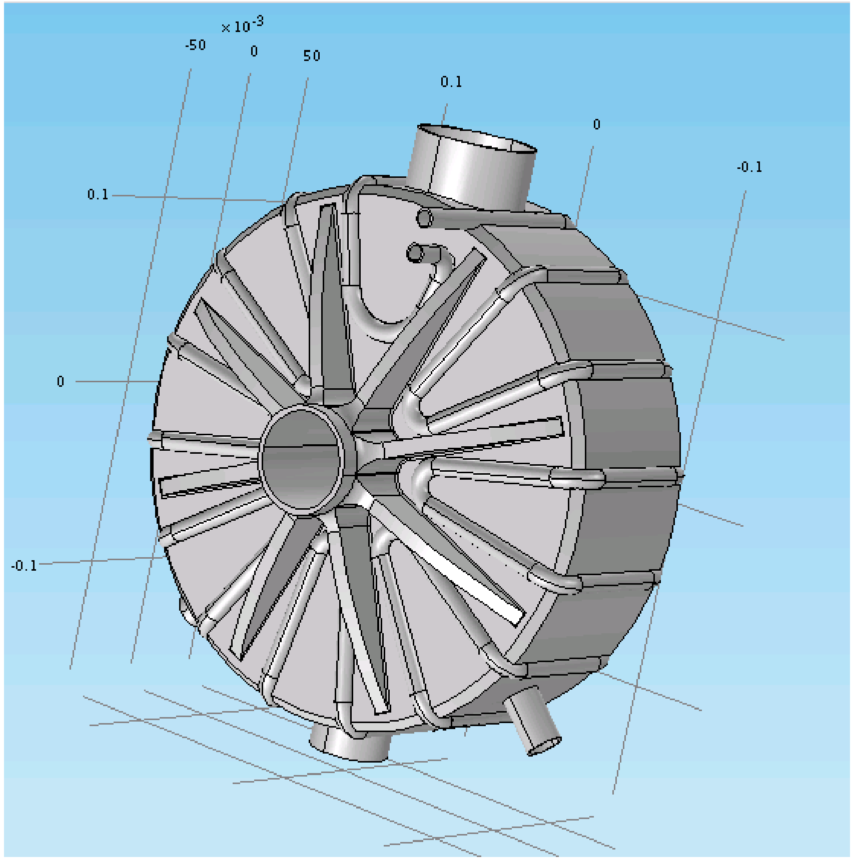


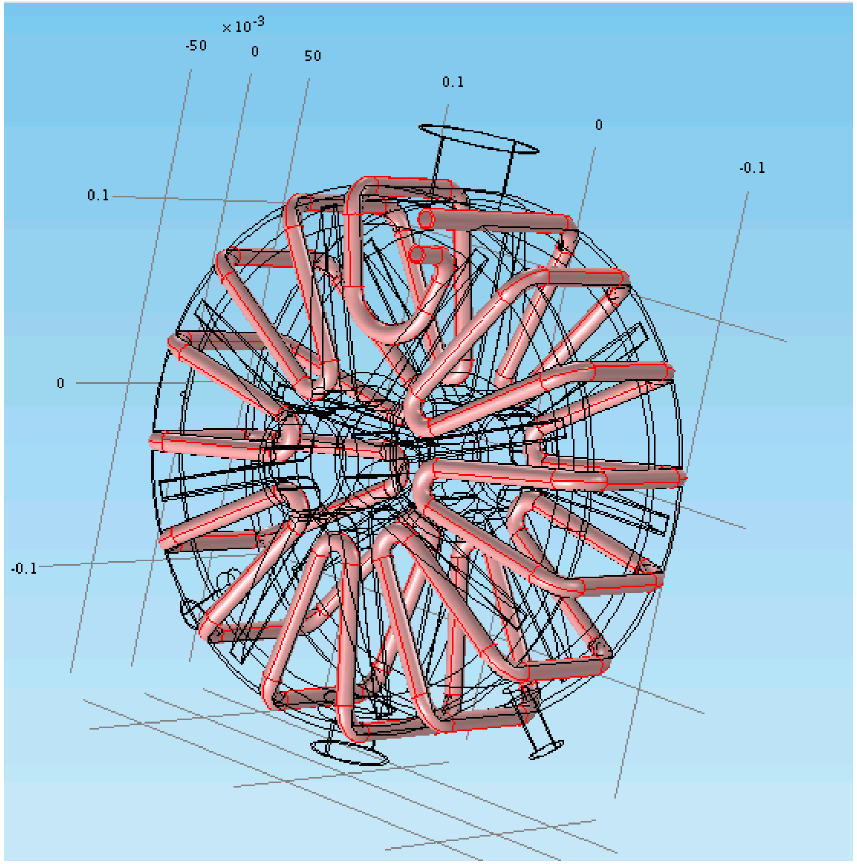




EM-Mechanical design

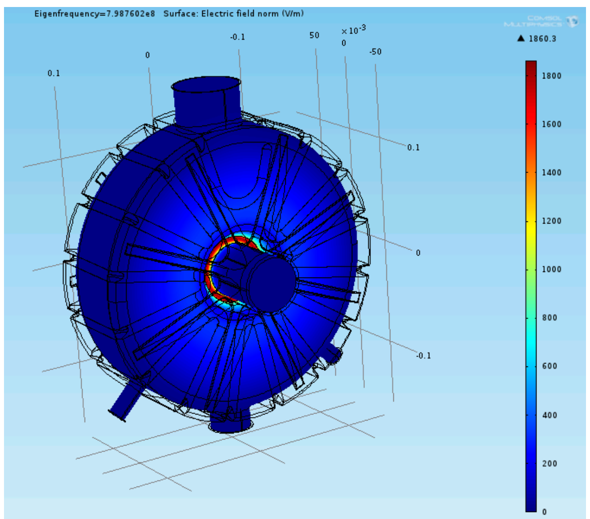
- After several iterations, a mechanical model was built by IJCLab (SM, 241217 model):





EM-Mechanical design

- After several iterations, a mechanical model was built by IJCLab (SM, **241217 model**):
  - f_resonance = 799.1697 MHz
  - Scaling to V0T/Lcav = 1.4 MV/m → Depends on Lcav in model



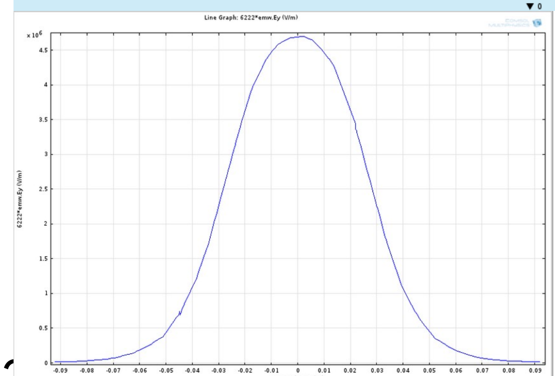
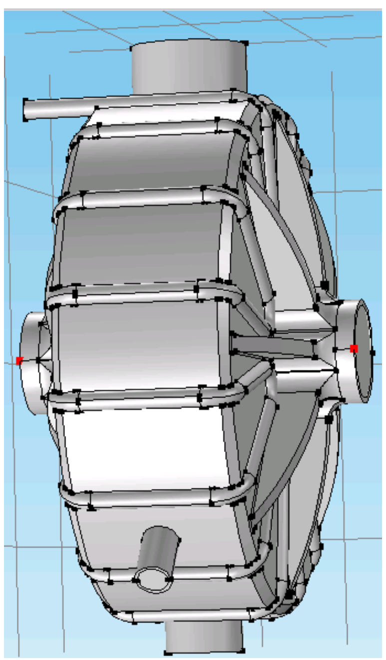


Table 3: Comparison of Figures of Merit

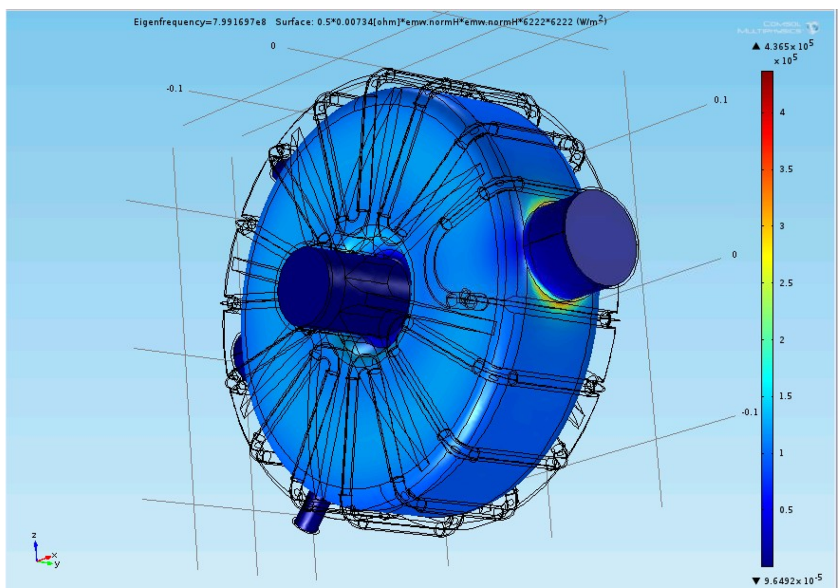
Figure of Merit	**ELCANO 2.5D**	**COMSOL 3D** (no ports)	**COMSOL 3D 241217 Model**	**241217 Model** 1.6 kW
$L_{cav}(m)$	0.126	0.126	0.126	0.126
Gradient (V_0T/L_{cav})	1.4 MV/m	1.4 MV/m	1.4 MV/m	0.608 MV/m
RF frequency	801.127 MHz	801.125 MHz	799.170 MHz	=
TTF	0.89	0.89	0.887	=
Power loss	8396 W	8419 W	8463 W	1596 W
Q0	22004	22145	22063	=
RsTT = $(V_0T)^2/P_{loss}$	3.706 MΩ	3.696 MΩ	3.675 MΩ	=
ZTT	29.4 MΩ/m	29.3 MΩ/m	29.17 MΩ/m	=
E_{surf_max}	8.78 MV/m	9.35 MV/m	10.38 MV/m	4.51 MV/m
E_{z_max}	3.2 MV/m	3.2 MV/m	3.225 MV/m	1.4 MV/m

EM-Mechanical design

- Power losses depends on definition of required power level:
  - Scaling to V0T/L = 1.4 MV/m, Lcav = 0.184 → Int. power loss= **18 kW**
  - Scaling to V0T/L = 1.4 MV/m, Lcav = 0.126 → Int. power loss= **8.4 kW**
  - Scaling to V0 = 200 kV → Int. power losses = **8.5 kW**
  - Scaling to Ez(z)_max = 1.4 MV/m → Int. power losses = **1.6 kW**

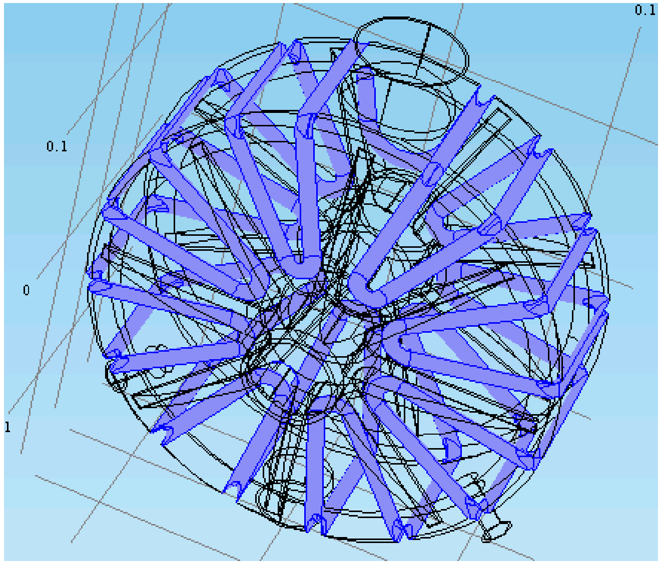


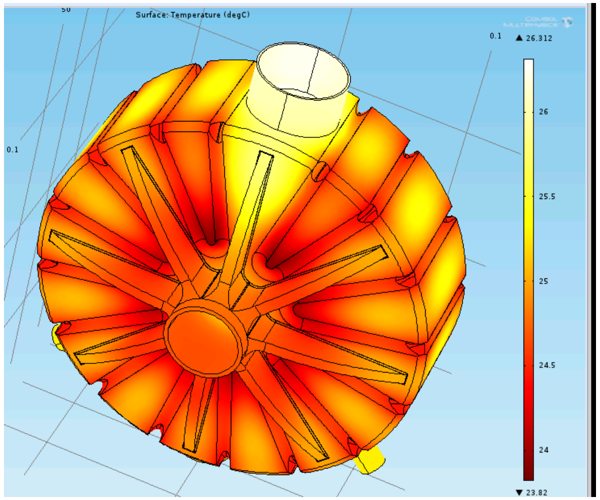
L_cav = 0.184 m



Definition of cavity required power should be clearly specified!

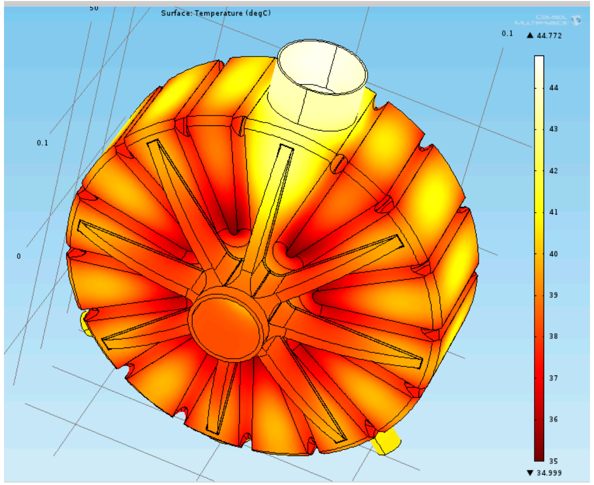
EM-Mechanical design





Ploss = 1600 W, Tmax = 26 degC

Using a h=5000 W/m2

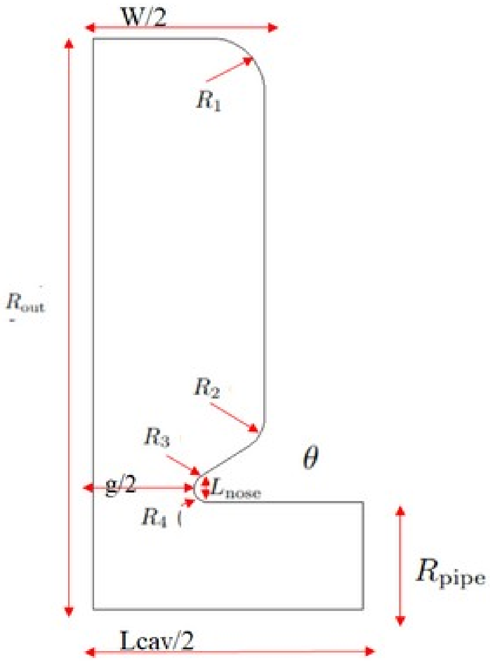


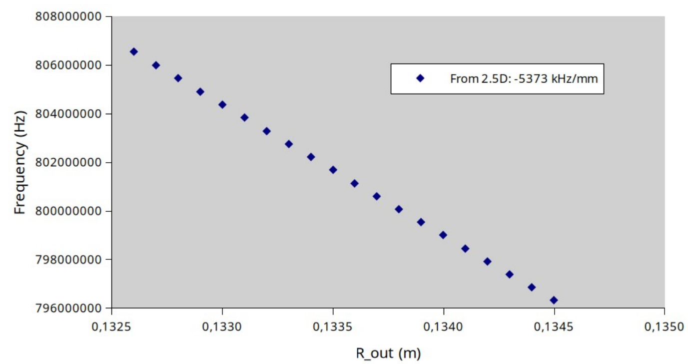
Ploss = 6266 W, Tmax = 45 degC

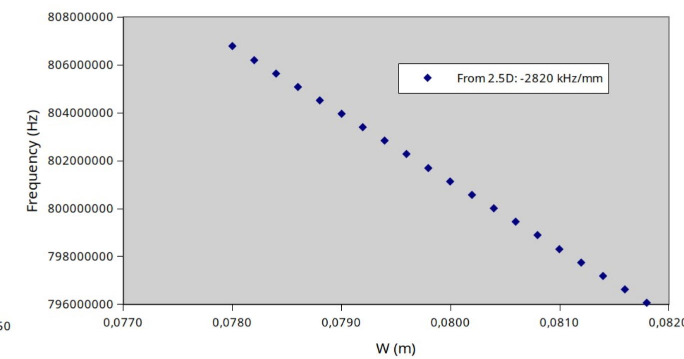
EM geometrical frequency sensitivity

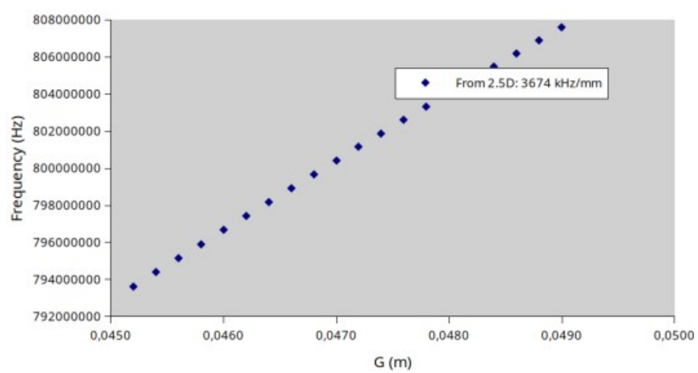
Using axisymm. simulations

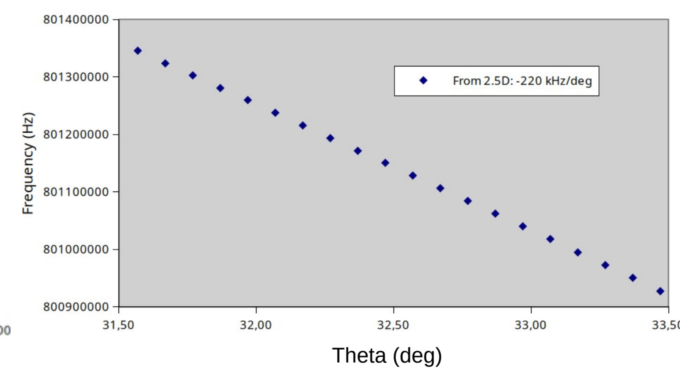
R out at ± 1mm
W/2 at ± 1mm
G/2 at ± 1mm
θ at ± 1 degre











Buncher cavity design

- Electromagnetic cavity design, remaining activities
  - Calculations with final specifications
  - 3D electric field asymmetries analysis (influence on beam emmitance)
  - Thermo-mechanical frequency detuning
- Coupler design and optimization
- Tuning considerations

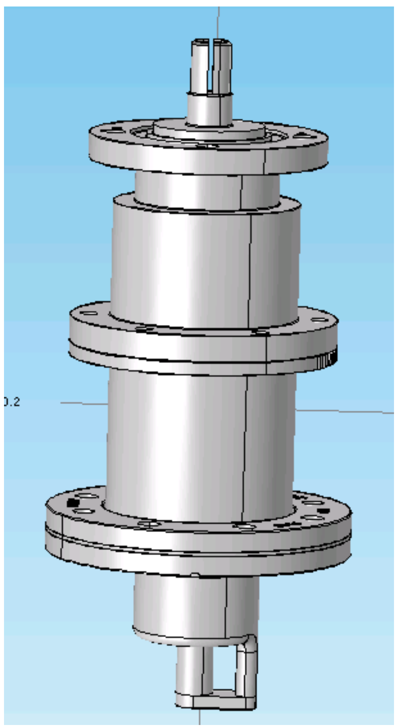
PERLE buncher CONCEPTUAL approach to coupler and tuning

(IJCLab, Orsay, 30 Jan 2025)

J. L. Muñoz
ESS-Bilbao
30.January.2025

Buncher coupler conceptual design

- Coaxial coupler pre-design, based on ESS MEBT bunchers
  - Alumina window, brazed
  - Coaxial dimensions would require optimization for S11
  - No active cooling (this would need to change)



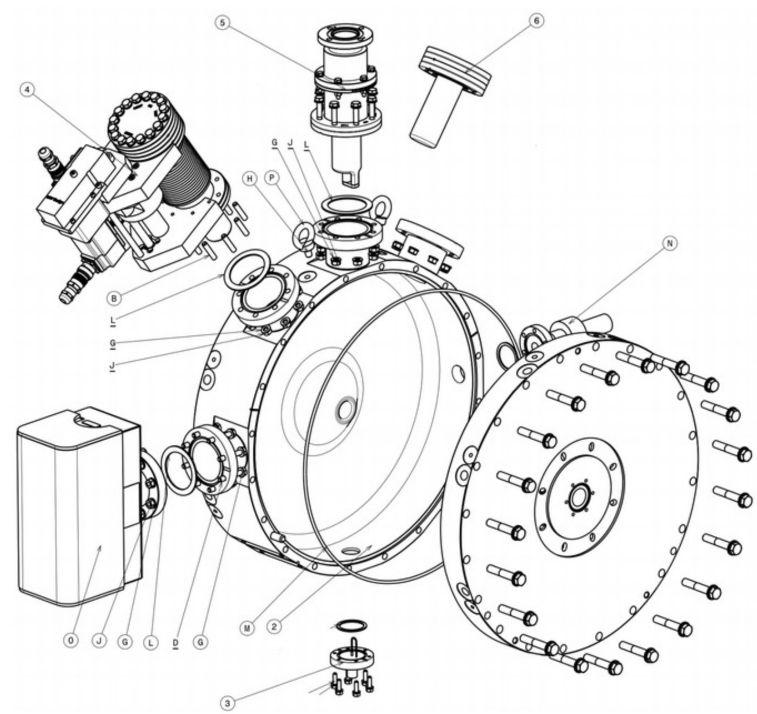


Figure 2: Buncher cavity drawing indicating main parts: Cavity body (2) cavity cover (1), vacuum pump (0). Motion control system (4). RF Coupler (5), Pick-up (3), Fixed Tuner (6).

ESS MEBT buncher system, with coupler, fixed tuner and motor tuner. EIA 1-5/8'' coaxial connection to SSPA

Buncher coupler conceptual design

- Coaxial coupler pre-design, based on ESS MEBT bunchers
  - Alumina window, brazed
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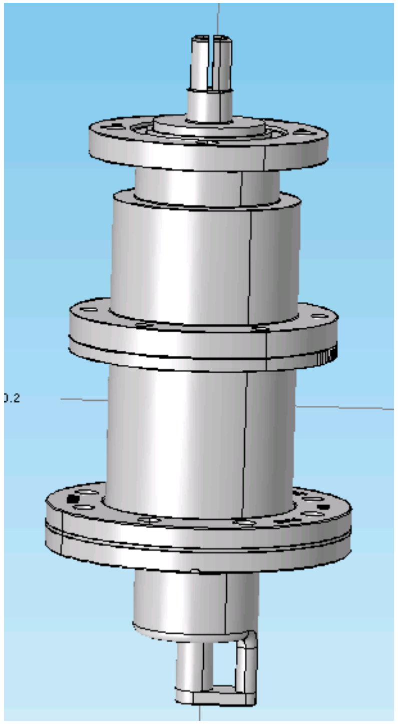
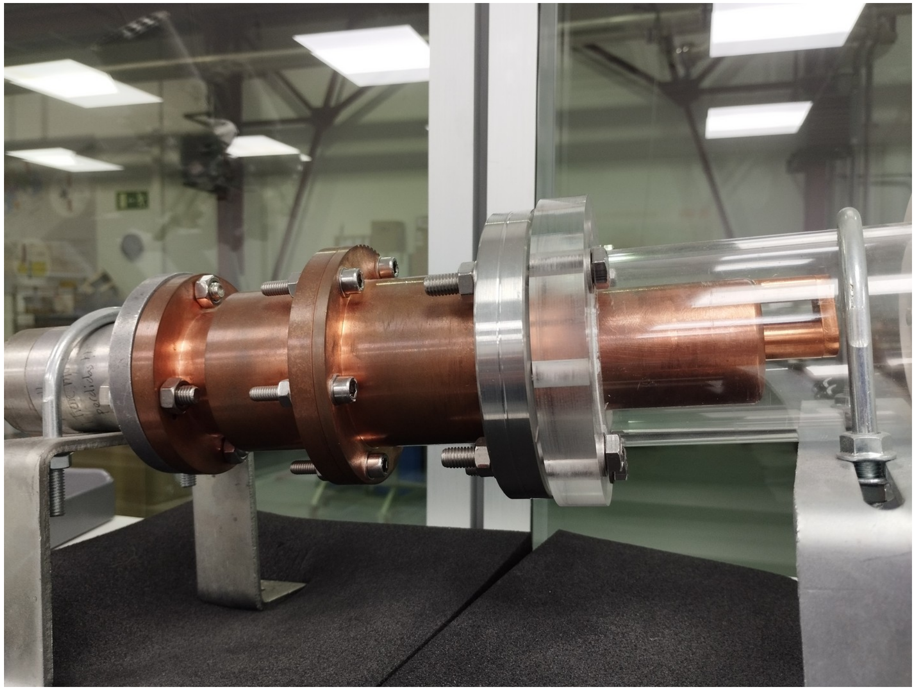
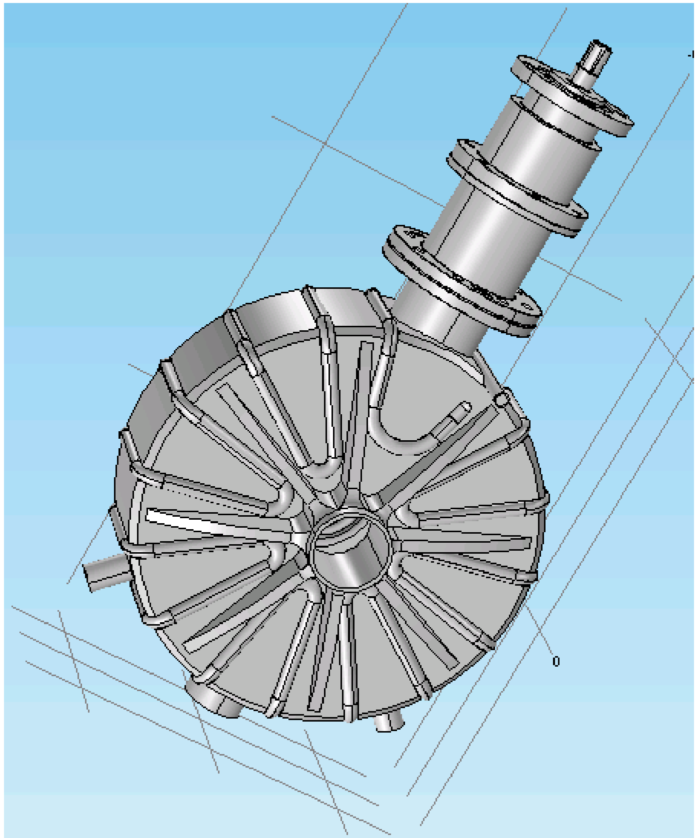
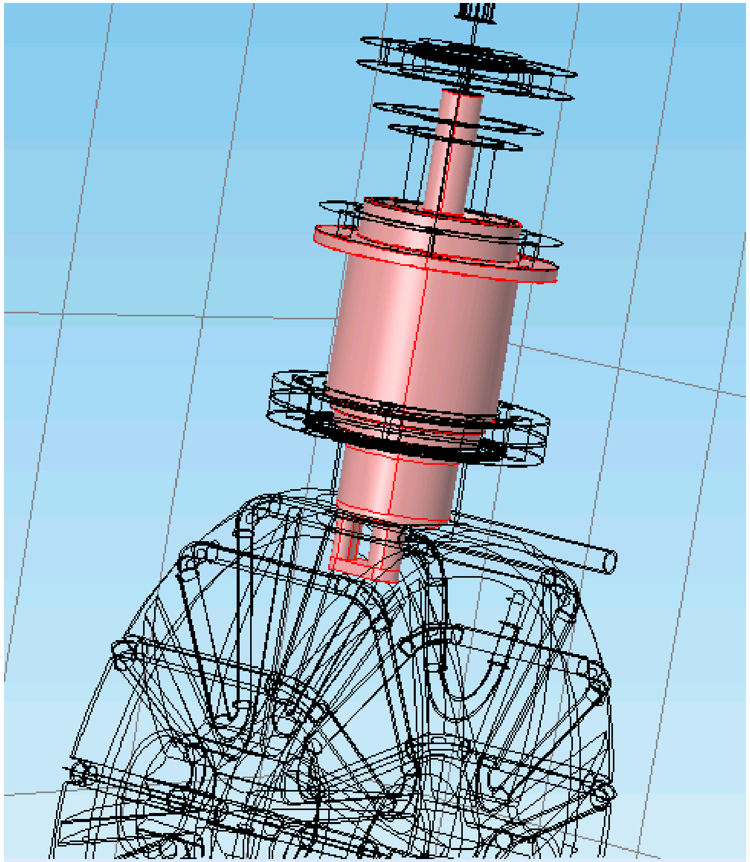




Buncher coupler conceptual design

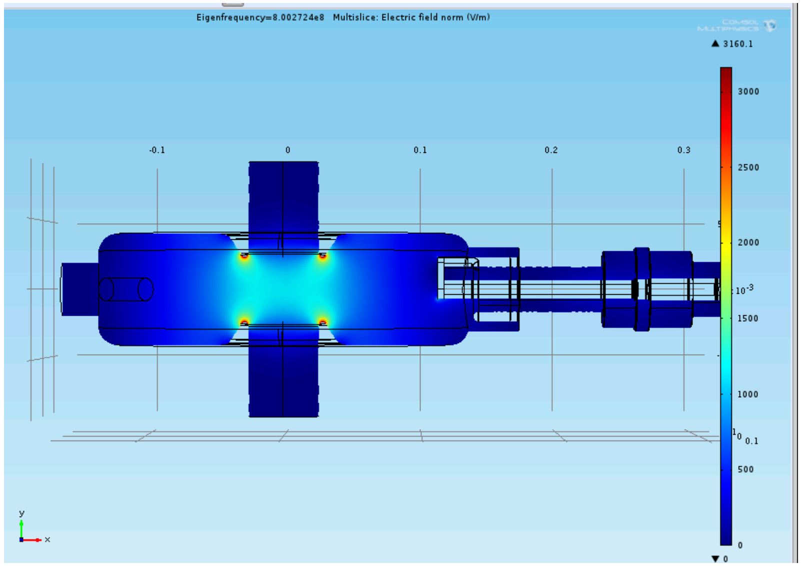
- Coaxial coupler pre-design, based on ESS MEBT bunchers

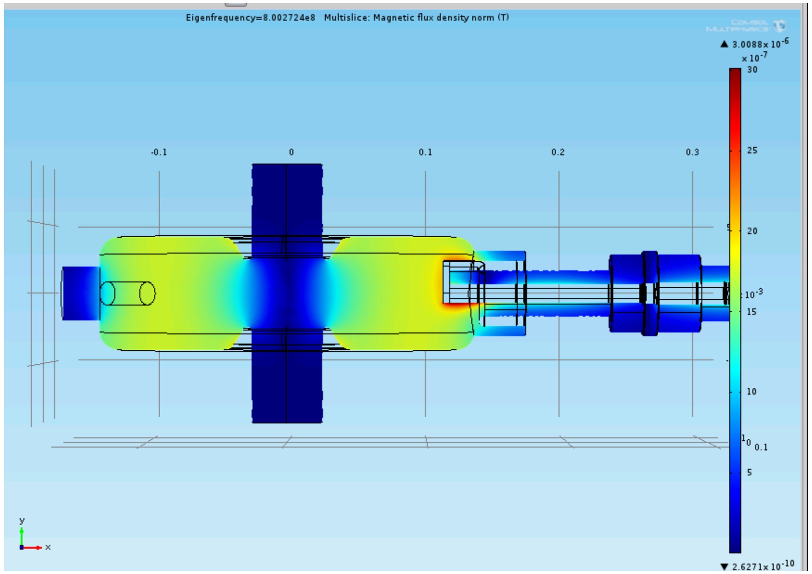




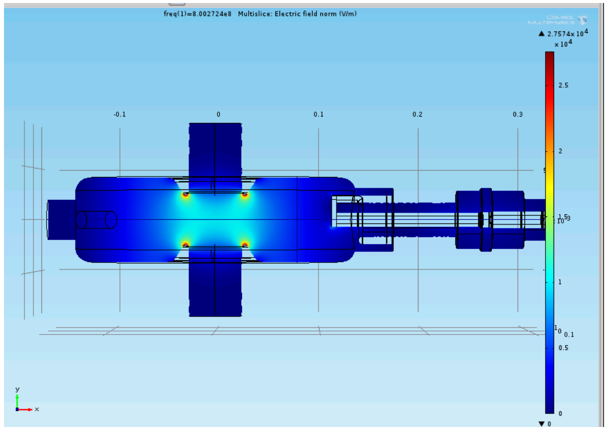
Buncher coupler conceptual design

- Coaxial coupler pre-design, based on ESS MEBT bunchers
  - Eigenfrequency calculations





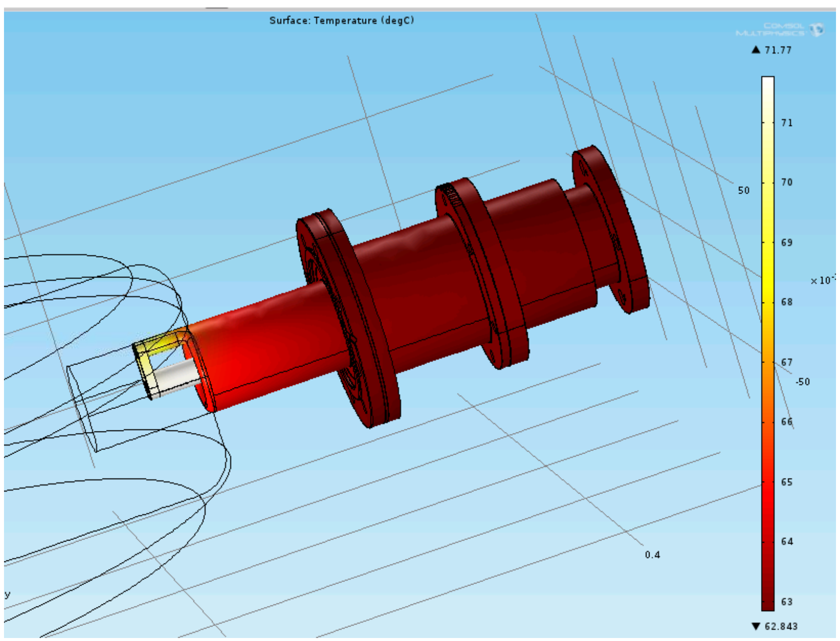
  - Frequency mode calculations (f=800 MHz). Couples, but S11 close to 0 dB

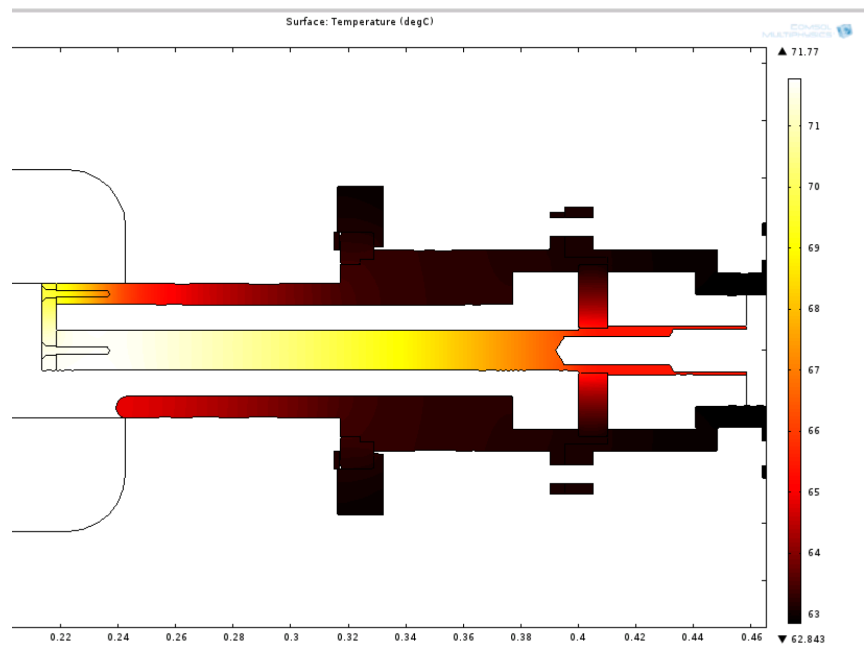


Coupler is optimized for 352.2 MHz, not 800 MHz. Alumina window and matching section should be redefined if this solution is chosen.

Buncher coupler conceptual design

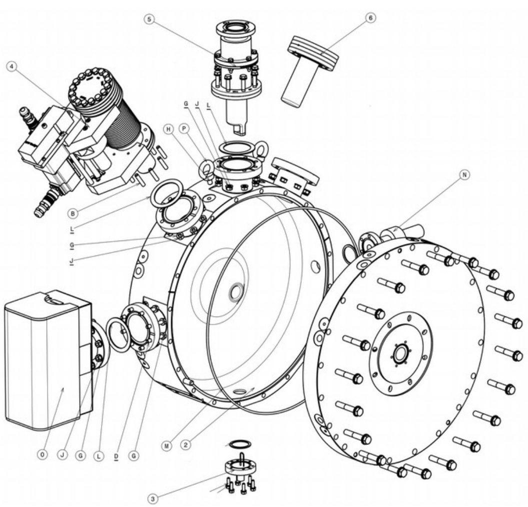
- Temperature is OK with no cooling for 1850 W (and optimum matching)
- Tmax = 72 degC (no active cooling)
- Maybe a PERLE buncher coupler design based on this concept is worth studying
  - (Matching section for alumina region and 800 MHz should be redefined)





Buncher tuner conceptual design

- Plunger tuner is a reliable method for frequency tuning.
- Tuners can be of fixed position or movable, connected to a motor and LLRF system
- Vacuum levels < 10^-9 mbar can be achieved using metallic o-rings.



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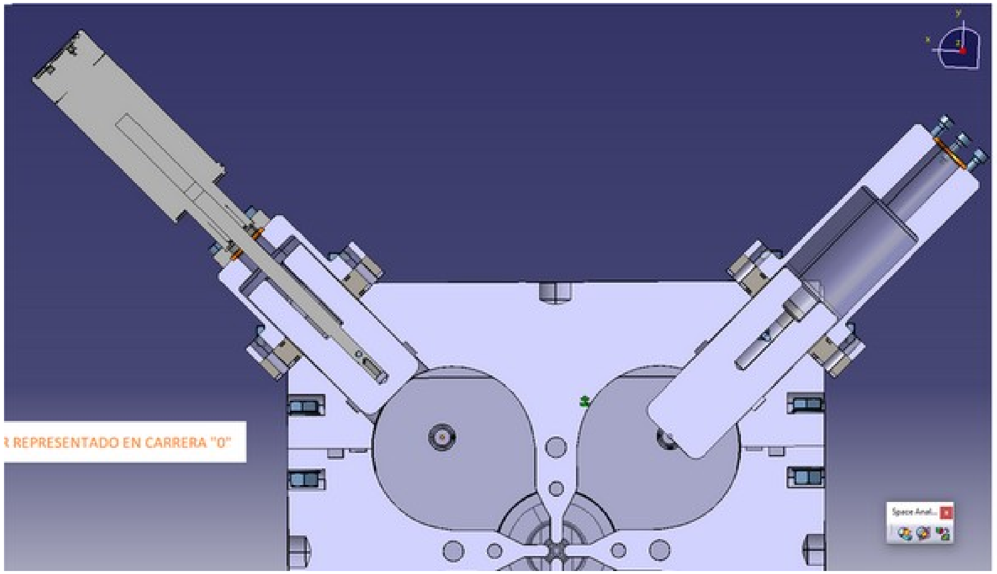

ESS-Bilbao RFQ tuners 36.6 mm diameter

Buncher tuner conceptual design

- Tuner frequency effect (in cERL buncher model. Results will be different in the nose-cone buncher):