PERLE buncher preliminary design

J. L. Muñoz
ESS-Bilbao
Genève, 22.June.2023

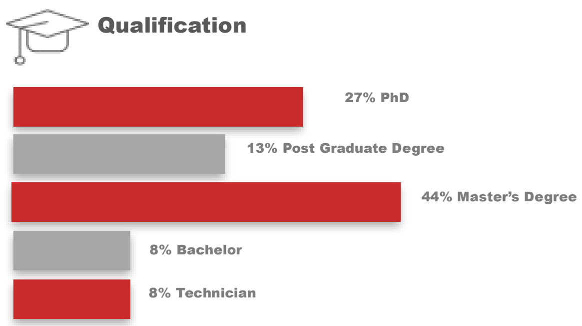
Contents

- Intro to ESS-Bilbao (3 slides)
  - ESS project (MEBT, RF, target, MIRACLES)
  - Local project: ARGITU
- Buncher cavities projects (2 slides)
  - ESS MEBT buncher cavities (protons, 352.2 MHz, duty cycle 5%)
  - ISRS (ISOLDE) (MHB, heavy ions, 10.128 MHz, duty cycle 10%)
- PERLE buncher pre-design
  - General specifications, similar designs
  - Computational tools used
  - First results of a pre-design of the buncher: electromagnetic optimization, cooling concept simulation
  - Future activities...

ESS-Bilbao

Consorcio ESS Bilbao

Public consortium of Central and Basque Governments; bringing knowledge and added value in particle accelerators and neutron scattering science and technologies; by leveraging its in-kind contribution to the European Spallation Neutron Source, in Lund (Sweden).



Headquarters

Parque Tecnológico
Zamudio (Bilbao)

R&D Center

Parque Tecnológico
Zamudio (Bilbao)

AWF

Polígono Industrial Júndiz
Vitoria-Gasteiz

Madrid Satellite

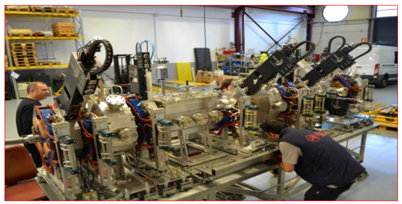
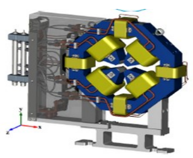
Instituto de Fusión Nuclear
Madrid

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN
EUSKO JAURLARITZA GOBIERNO VASCO

ESS-Bilbao

Main activity: Spanish in-kind contribution to ESS project (MEBT, RF, Target station, MIRACLES instrument)

MEBT

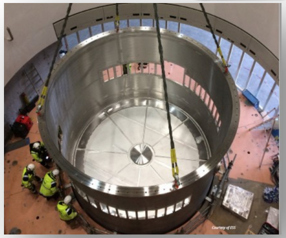




Accelerating element: complete subsystem that goes after the RFQ and integrates: design, manufacturing, diagnostics, control, assembly and testing.

RF Systems

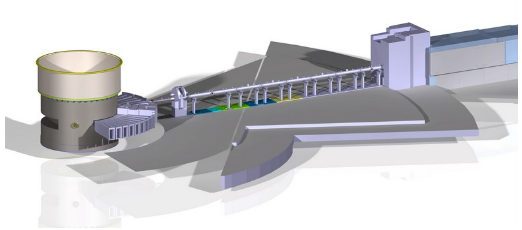
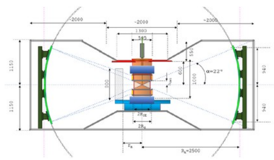
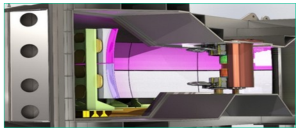

RF chains: 1 for RFQ and 5 for DTL. Composed by klystrons, modulators, loads, waveguides, interlocks and LLRF

TARGET

The spallation process takes place when the accelerated proton beam hits the Tungsten bricks of the 11-tonne target wheel. This will produce neutron brightness for scientific experiments across multiple disciplines.

MIRACLES INSTRUMENT

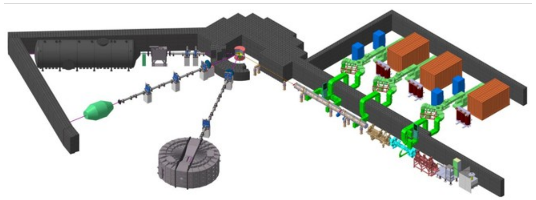
Time-of-Flight backscattering instrument for polymer science, energy materials, and magnetism studies.
Prime contractors: design, manufacturing, assembly &cold commissioning

EUROPEAN SPALLATION SOURCE

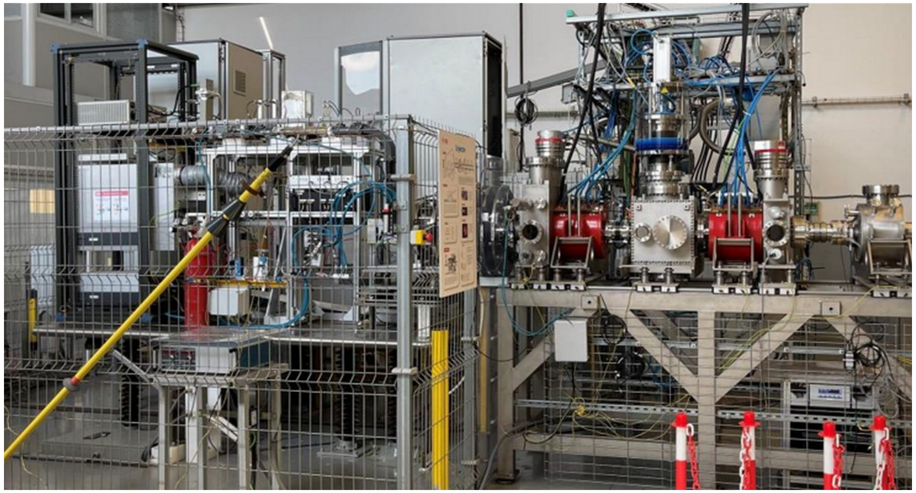
ESS-Bilbao

Local project: ARGITU CANS (Compact Accelerator-driven Neutron Source)

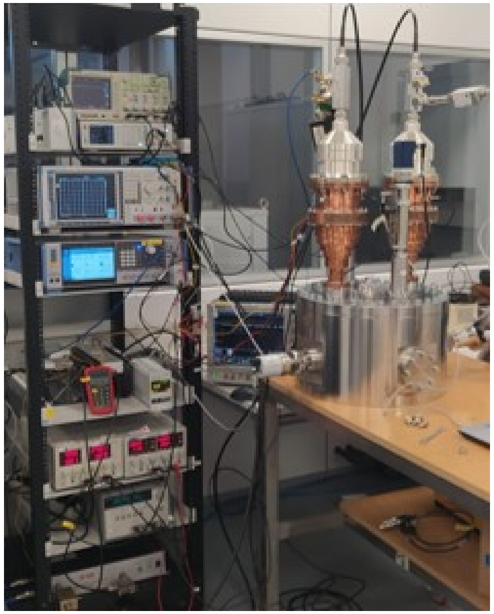
- ARGITU is part of European Low Energy accelerator-based Neutron (**ELENA**) Association.
- ARGITU Accelerator a multi-purpose machine that could provide 30 MeV proton beam.
- The proposed neutron source will have up to 4 instruments per target station, it could be possible to consider a dedicated moderator per instrument.



More info: M. Perez et al., "ARGITU compact accelerator neutron source: A unique infrastructure fostering R&D ecosystem in Euskadi", Neutron News, Vol. 31, issue 2-4, pp. 19-25, Dec. 2020, (https://doi.org/10.1080/10448632.2020.1819140)



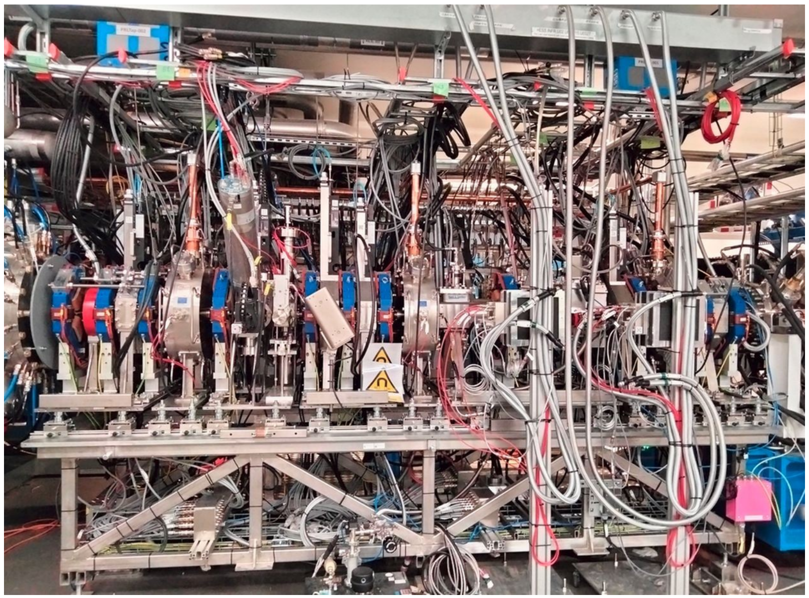
Injector (H^+, He, N), ion source + LEBT (45 keV)

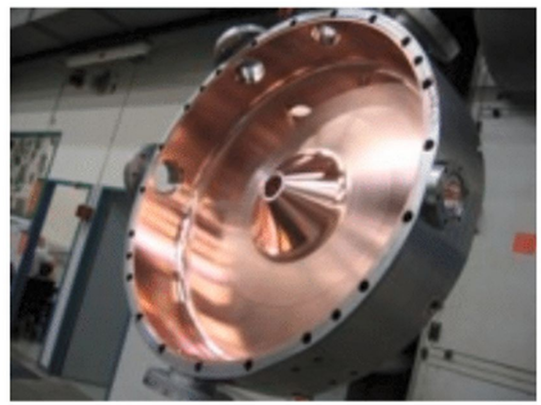


RFQ under fabrication (3 MeV) and testing

Buncher cavities projects

- **<u>ESS MEBT buncher cavities</u>**. From scratch design -> fabrication -> conditioning -> installation





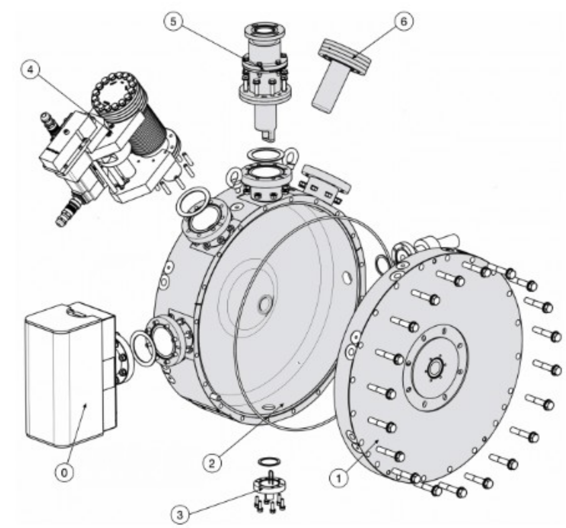


Figure 2. RF Buncher cavity drawing indicating main parts: vacuum pump (0), cavity cover (1), cavity body (2), RF pick-up (3), movable tuner and its motion control system (4). RF Coupler (5), fixed Tuner (6).

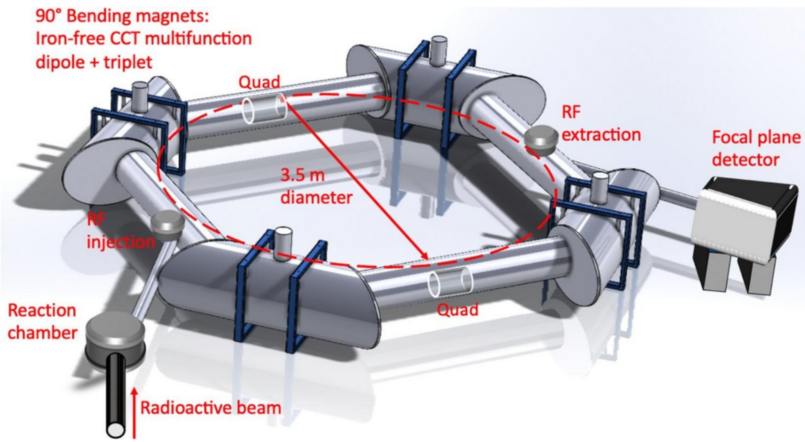
I. Bustinduy et al. "ESS MEBT: an overview" Nuclear Instruments and Methods A 00 (2023) 1–17

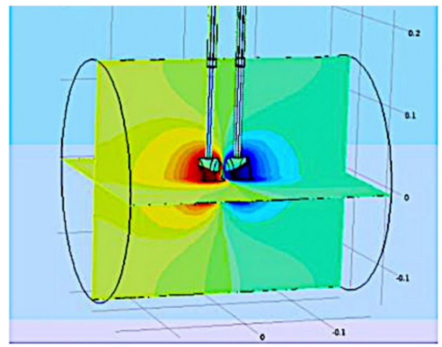
Buncher specifications:

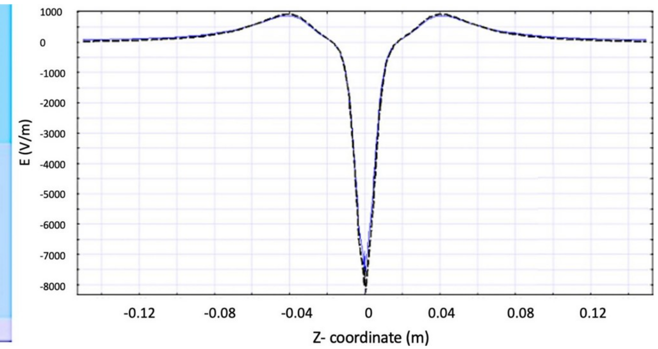
- *Specimen: H^+, 3.62 MeV*
- *Intensity: 62.5 mA*
- *Frequency: 352.2 MHz*
- *Duty cycle: 5%*
- $E_0TL = 150\ kV$
- $L_{f2f} = 190\ mm$

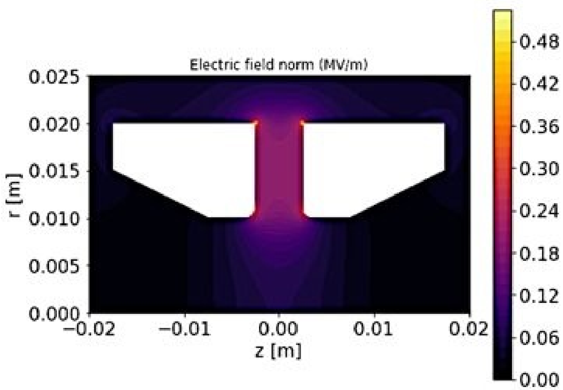
Buncher cavities projects

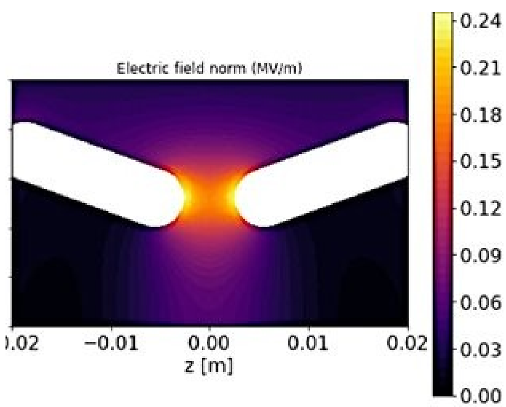
- **ISRS** (ISOLDE Superconducting Recoil Separator) project
- A **MHB** (MultiHarmonic Buncher) is proposed to compact HIE-ISOLDE bunch and inject in the ring

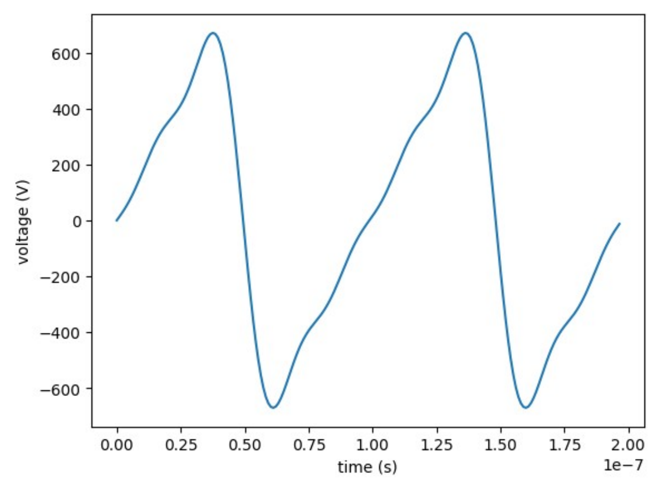










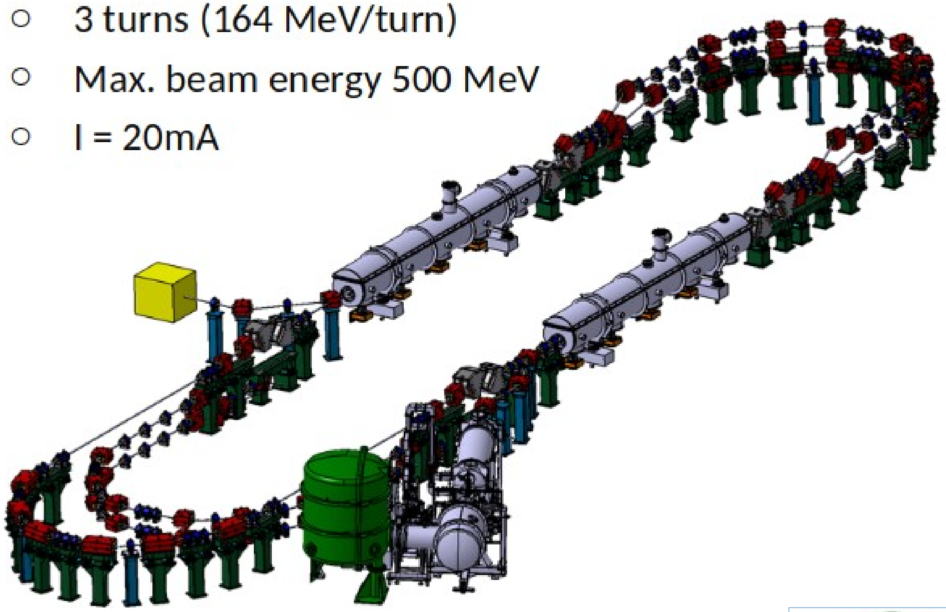


I. Martel et al. "An innovative Superconducting Recoil Separator for HIE-ISOLDE", (https://doi.org/10.1016/j.nimb.2023.05.052.)

PERLE project

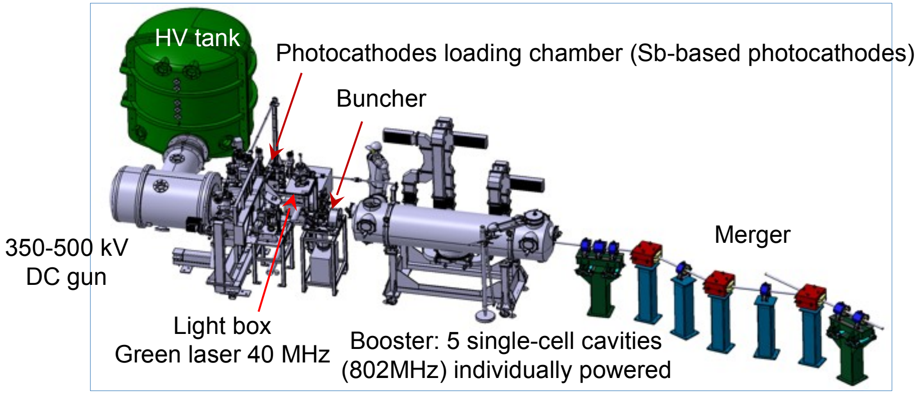
Main challenges: Multi-turn, high bunch charge, high power energy recovery, …

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (164 MeV/turn)
- Max. beam energy 500 MeV
- I = 20mA



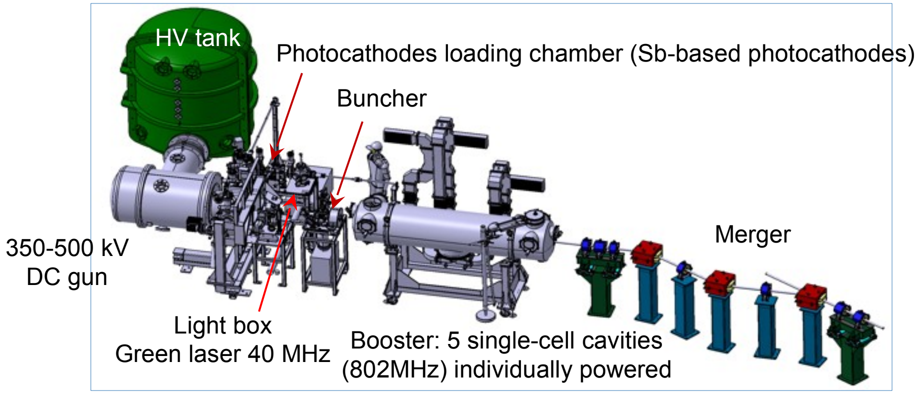
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

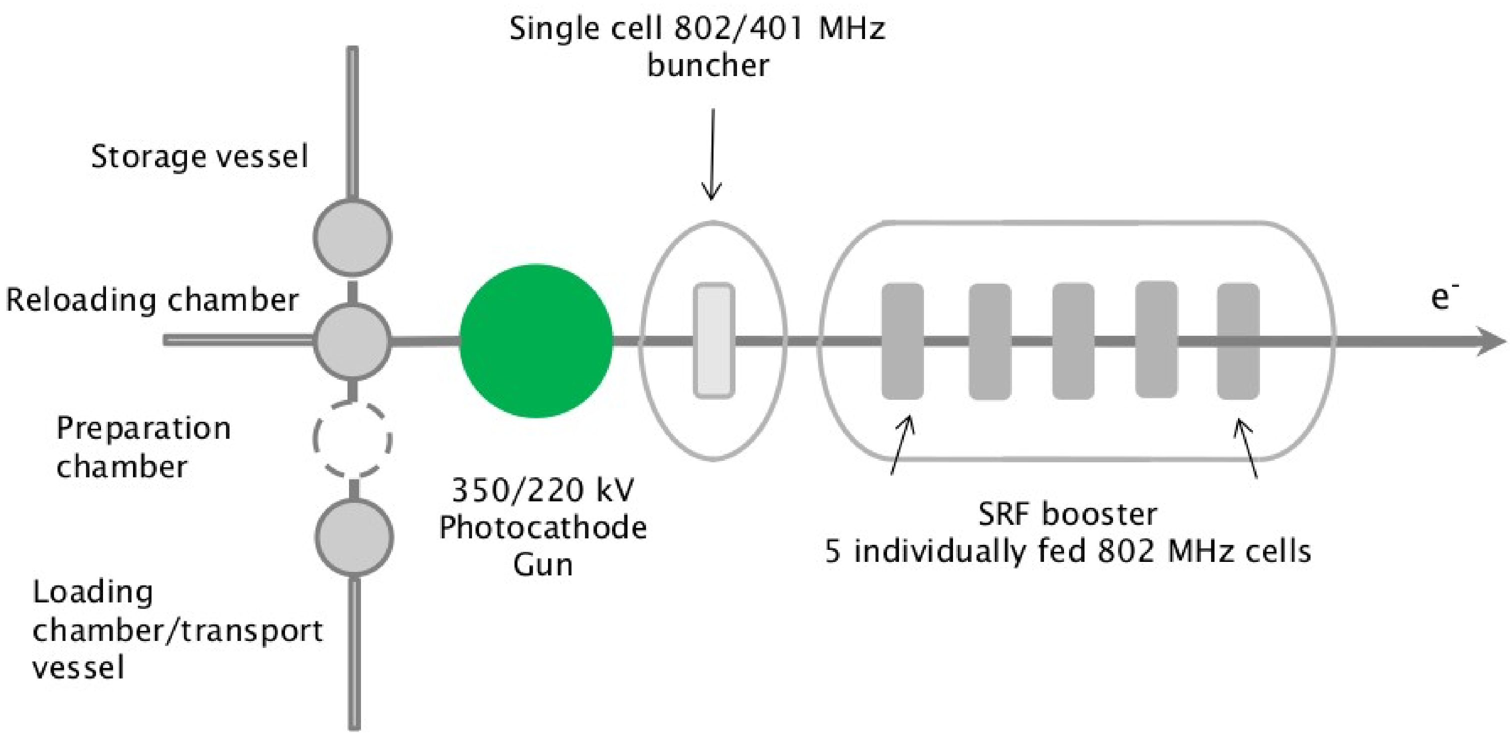
Injection line delivering 500pC bunches at 7 MeV.



“PERLE Status & Plans- October 27th 2022.pptx” (Walid KAABI, LHeC/FCCeh and PERLE Workshop, Orsay October 27th 2022

PERLE buncher



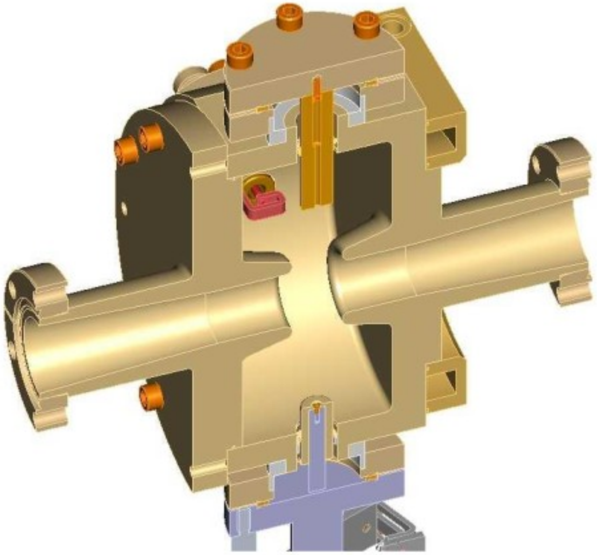


PERLE Conceptual Design Report, https://arxiv.org/pdf/1705.08783.pdf

PERLE buncher similar designs

Buncher

- The buncher cavity is an 802 MHz normal conducting cavity.
- The field map used for the beam dynamics simulations is a scaled version of the 1.3 GHz ALICE buncher.
- For the next iteration a more realistic buncher cavity design will be needed.
- The possibility of a 401 MHz cavity will be investigated and may help reduce the curvature of the longitudinal phase space.



1.3 GHz ALICE buncher

Design of the PERLE injector Ben Hounsell LHeC/FCC-eh workshop 27/06/18

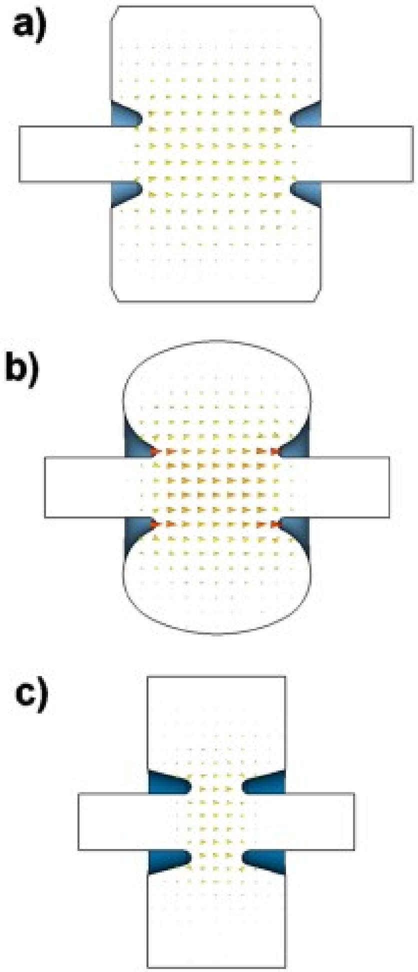
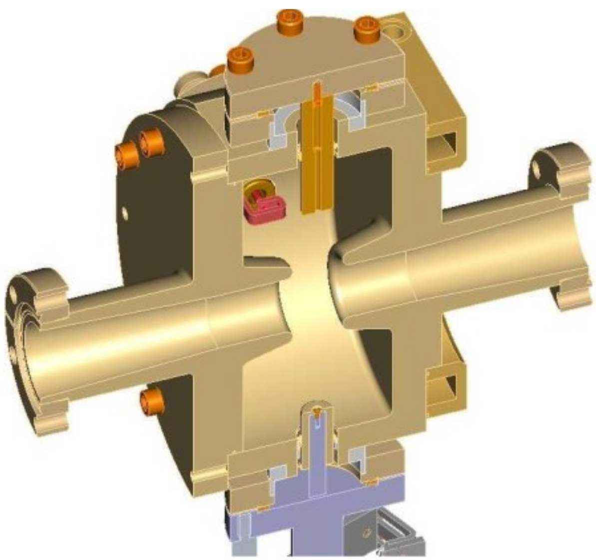
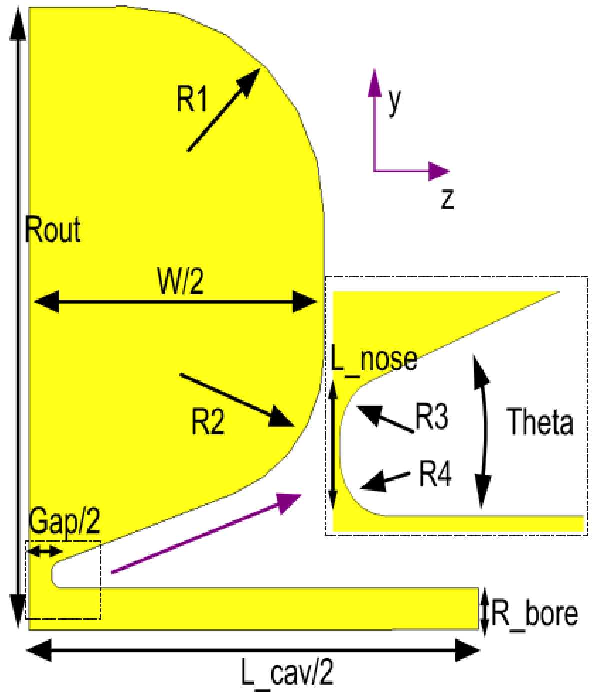


Figure 1: Cavity field plots for the fundamental frequency for a) the EU cavity, b) the Cornell cavity and c) the ELBE cavity (for further explanation see text).

PERLE buncher pre design



1.3 GHz ALICE buncher



ESS-MEBT buncher parametrization

The RF frequency is 801.56 MHz
According to beam dynamics simulations, operating gradient is in the order of 1.4 MV/m
The cavity is in copper at room temperature. So you will have to make the cooling system.
I think that a single cell is enough but you are free in the design of the buncher, if you think that 2 cells are better do it.
The diameter of beam pipe 50 mm.
I know that you used to design RF cavities but I must give you some requirements nevertheless :

1. Minimize the RF power
2. Minimize breakdown hazards by minimizing the peak electrical field
3. The coupling of the cavity with the RF network must be set in such a way that the reflection is as low as possible, S11 < -20 dB and that in presence of beam
4. Correlated to the previous point, you will have to calculate the beamloading and to compensate it.

The nominal electron beam current is 20 mA with 500 pC per bunch at 40 MHz.

(email R. Roux, 27/04/2023)

PERLE buncher pre design

RF design tools:

- ELCANO computational electromagnetism suite (ESS-Bilbao).
  - Python driven, based on OpenCASCADE, GMSH, FEniCSx, SLEPc.
  - Easily fully parallelized (in cluster) for quick parametric/optimization studies
  - 2D, 2.5D, 3D. Eigenfrequency, frequency domain, time explicit (wakefields, …)
- COMSOL Multiphysics
  - Full multiphysics simulations: RF+Thermomechanical+cooling+Mesh deformation+…
  - Simulations of whole cavity system
- Beam dynamics codes: GPT, Tracewin...

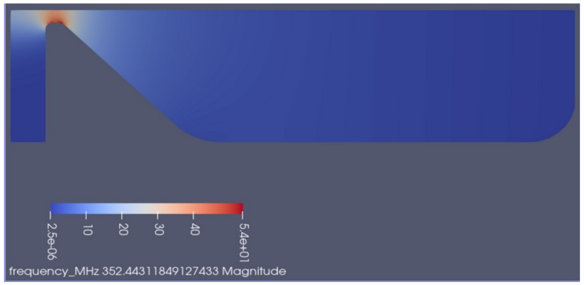
Buncher parameters

```
def get_mebt_buncher_parameters ():
    p=dict()
    p['R_pipe'] = 0.015
    p['g'] = 0.0122
    p['theta'] = 45
    p['R1'] = 0.020
    p['R2'] = 0.029
    p['R3'] = 0.0032
    p['R4'] = 0.0032
    p['W'] = 0.126
    p['R_out'] = 0.2425
    p['L_nose'] = 0.0072
    p['L_cav'] = 0.126
    #
    p['lc1'] = 0.002
    p['lc2'] = 0.001
    #
    p['beta'] = 0.08783
    p['rf_frequency'] = 352.21e6
    p['sigma'] = 58e6 # S/m
    p['gradient'] = 1.27e6 # V/m
    return p
```

Python scripting

```
p = get_mebt_buncher_parameters()
 x_opt = optimize_for_frequency (p, 'R_out', 0.15, 0.4, target_frequency=352.2e6)
print (get_frequency_model(build_mesh_buncher_nose_2da, p, 3e8))
build_mesh_buncher_nose_2da (p, gui=True)
merit = solve_and_get_figures_of_merit (build_mesh_buncher_nose_2da, p, target_frequency=352.2e6, plot=False)
print (merit)
```

Results and figures of merit




```
'half_lcav_computed': 0.063
'beta': 0.08783
'frequency': 352443118.49127436
'omega': 2214465423.720929
'lambda': 0.850612318048202
'V0': 248196.68372734485
'V0T': 160020.0
'T': 0.6447306128223257
'gradient_calc': 1270000.0
```

```
'We_J': 0.04106666423456959
'Wm_J': 0.04106666423408286
'power_loss_W': 15485.783243366…
'Q0': 23490.11518120659
'E_kilpatrick_MVm': 18.45576417…
'Emax_Vm': 26724391.626656607
'bravery_factor': 1.44802411723…
```

PERLE buncher pre design

PERLE buncher: conventional iterative design optimization route

```python
import perle_buncher as pb
import numpy as np

p=dict()
p['R_pipe'] = 0.025
p['g'] = 0.0122
p['theta'] = 45
p['R1'] = 0.005
p['R2'] = 0.005
p['R3'] = 0.0032
p['R4'] = 0.0032
#p['W'] = 0.126
p['W'] = 0.080
p['R_out'] = 0.2425
p['L_nose'] = 0.0072
p['L_cav'] = 0.126
#
p['lc1'] = 0.002
p['lc2'] = 0.001
#
p['beta'] = 0.8048
p['rf_frequency'] = 801.56e6
p['sigma'] = 58e6 # S/m
p['gradient'] = 1.4e6 # V/m
```

Design specifications

Parameters for design

Free parameter to match frequency

```python
gap=np.arange(0.020,0.080,0.001)
l_nose=np.arange(0.005,0.020,0.0025)
for g in gap:
    for lnose in l_nose:
        p=p_initial.copy()
        p['g']=g
        p['L_nose']=lnose
        x_opt=pb.optimize_for_frequency (p, 'R_out', 0.1, 0.4, target_frequency=801e6)
        p['R_out']=x_opt[0]
        merit=pb.solve_and_get_figures_of_merit (pb.build_mesh_buncher_nose_2da, p)
        fout=open(nameout,'a')
        if merit:
            freq=merit['frequency']
            grad=merit['gradient_calc']
            ploss=merit['power_loss_W']
            kilp=merit['bravery_factor']
        else:
            freq=0
            grad=0
            ploss=0
            kilp=0
        rout=p['R_out']
        fout.write (f'{g}\t{lnose}\t{rout}\t{freq}\t{grad}\t{ploss}\t{kilp}\n')
        fout.close()
```

PERLE buncher pre design

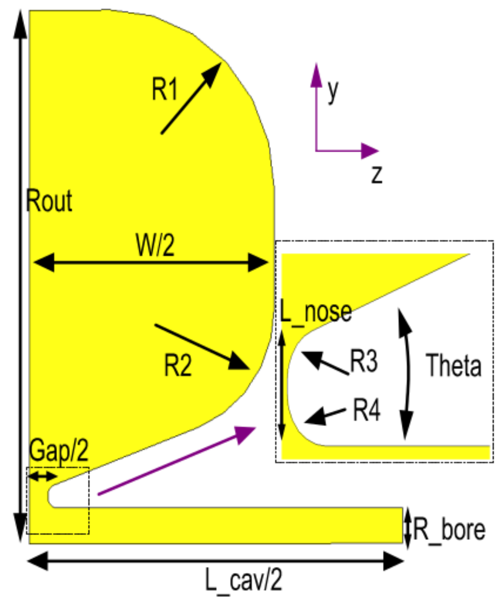
PERLE buncher: conventional iterative design optimization route (exploration to maximize effective shunt impedance, ZTT/L)

Parametric run #1

```
gap=np.arange(0.020,0.080,0.001)
l_nose=np.arange(0.005,0.020,0.0025)
for g in gap:
    for lnose in l_nose:
```

Parametric run #1

```
theta=np.arange(32.5,45,2.5)
radio_1=np.arange(0.0025,0.0125,0.0025)
radio_2=np.arange(0.0025,0.0125,0.0025)
for angle in theta:
    for r1 in radio_1:
        for r2 in radio_2:
```



Initial pre-design → Beam dynamics, multipacting,... → Mechanical, engineering constrains → Detailed design

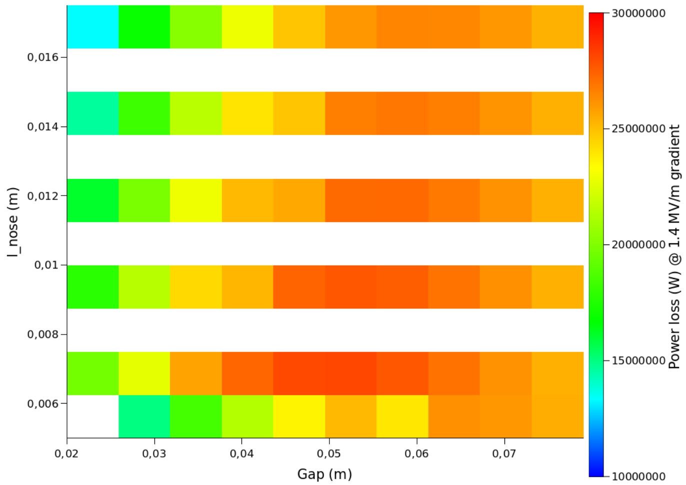
EM/BD optimization

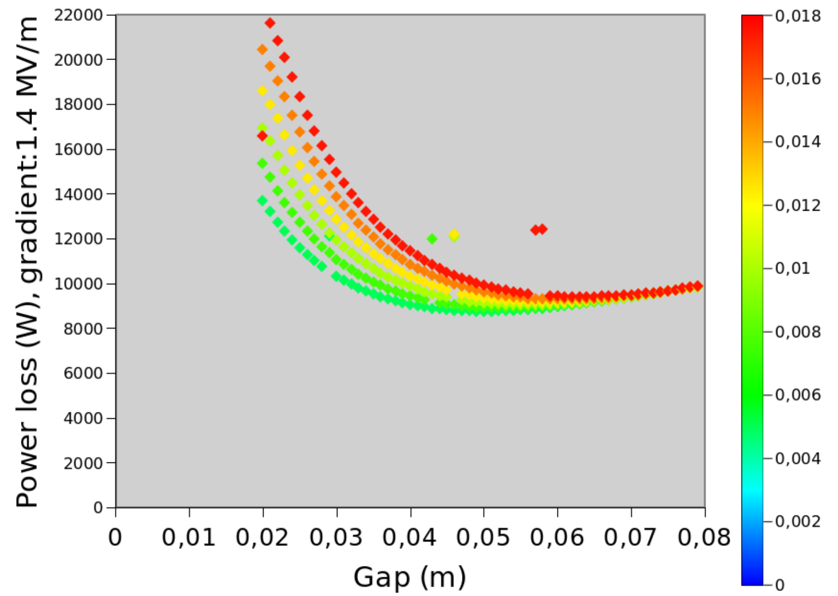
EM/BD optimization

EM/BD optimization

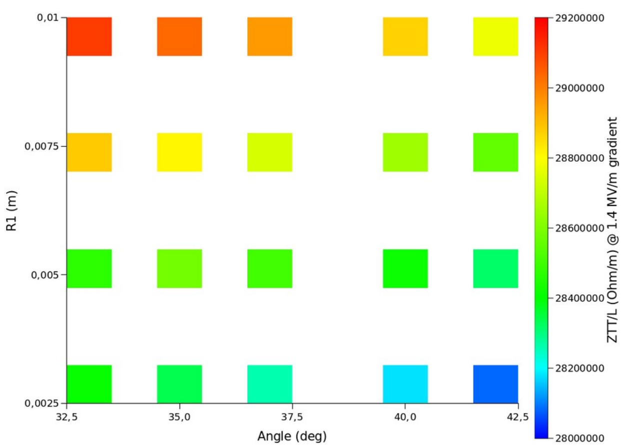
PERLE buncher pre design

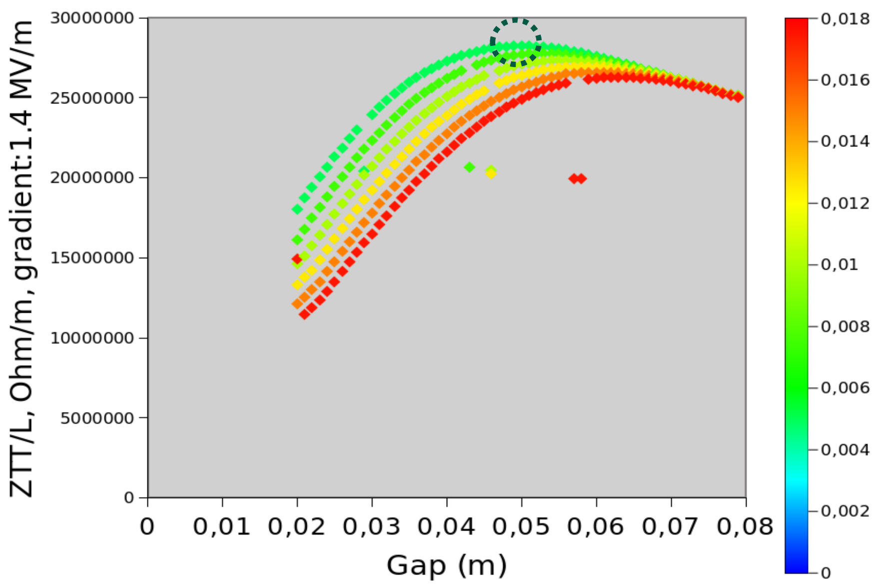
- Parametric run #1
  - gap + l_nose variation
  - ZTT/L maximization





- Parametric run #2
  - Theta, R1, R2





PERLE buncher pre design

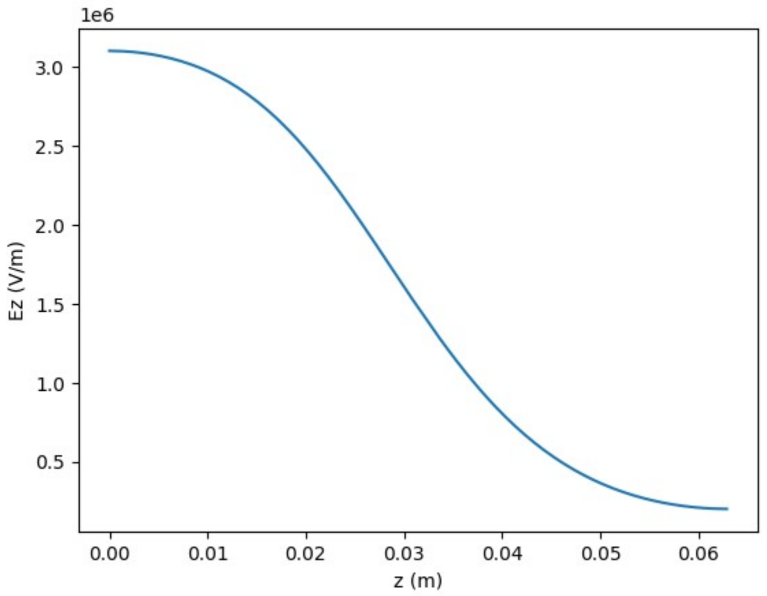
Set of parameters P1

```
'R_pipe': 0.025
'g': 0.05
'theta': 32.5
'R1': 0.01
'R2': 0.0075
'R3': 0.0032
'R4': 0.0032
'W': 0.08
'R_out': 0.1352
'L_nose': 0.005
'L_cav': 0.126
```

Figures of merit

```
'half_lcav_computed': 0.063
'beta': 0.8048
'frequency': 801048537.9800817
'omega': 5033136404.174138
'lambda': 0.3742500532563914
'V0': 199316.2723996594
'V0T': 176400.0
'T': 0.8850255820874033
'gradient_calc': 1400000.0
'We_J': 0.009288280951024378
'Wm_J': 0.009288280951007056
'power_loss_W': 8483.39275001584
'Q0': 22042.683329339947
'rsTT': 3667985.31164809
'ZTT': 29110994.5368896
'E_kilpatrick_MVm': 26.02185831…
'Emax_Vm': 9544109.914735898
'bravery_factor': 0.36677280307…
```

E_z (z)

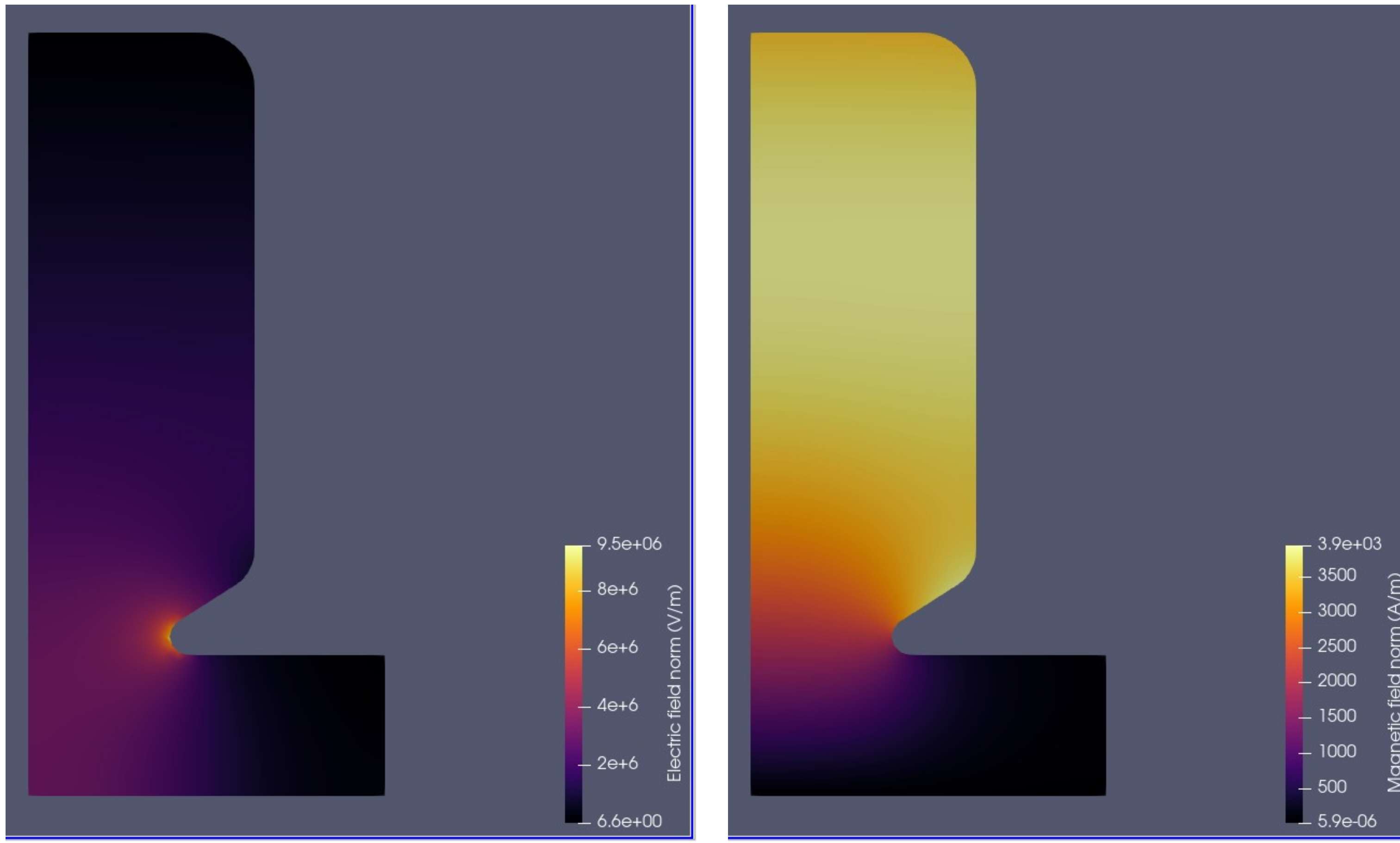


PERLE buncher pre design

Set of parameters P1

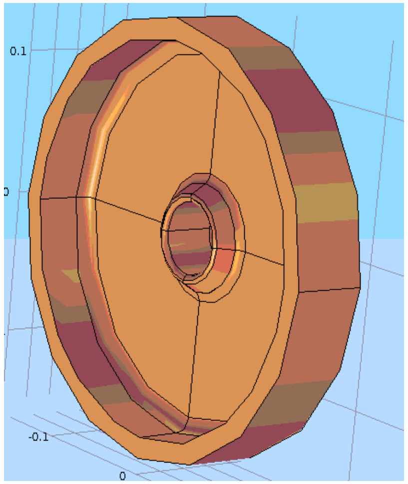
```
'R_pipe': 0.025
'g': 0.05
'theta': 32.5
'R1': 0.01
'R2': 0.0075
'R3': 0.0032
'R4': 0.0032
'W': 0.08
'R_out': 0.1352
'L_nose': 0.005
'L_cav': 0.126
```

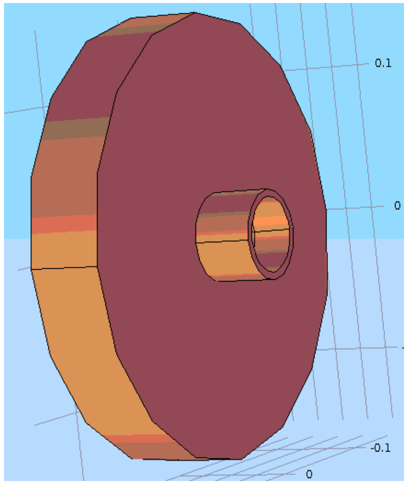
Electric and magnetic field maps

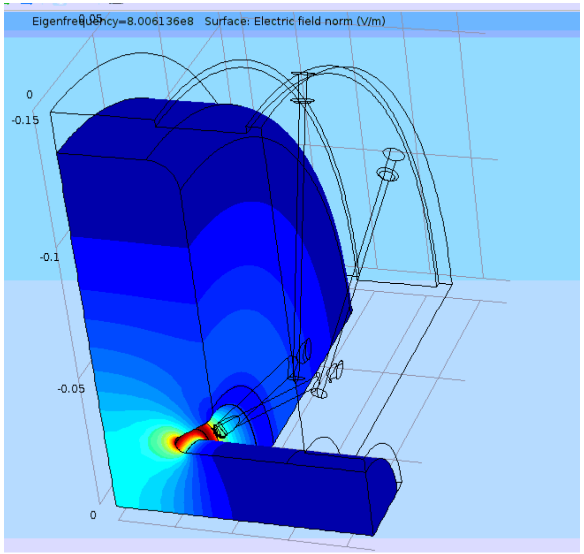


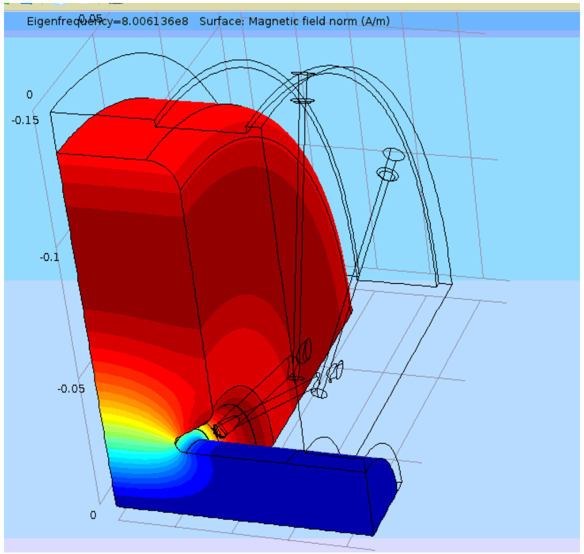
PERLE buncher pre design

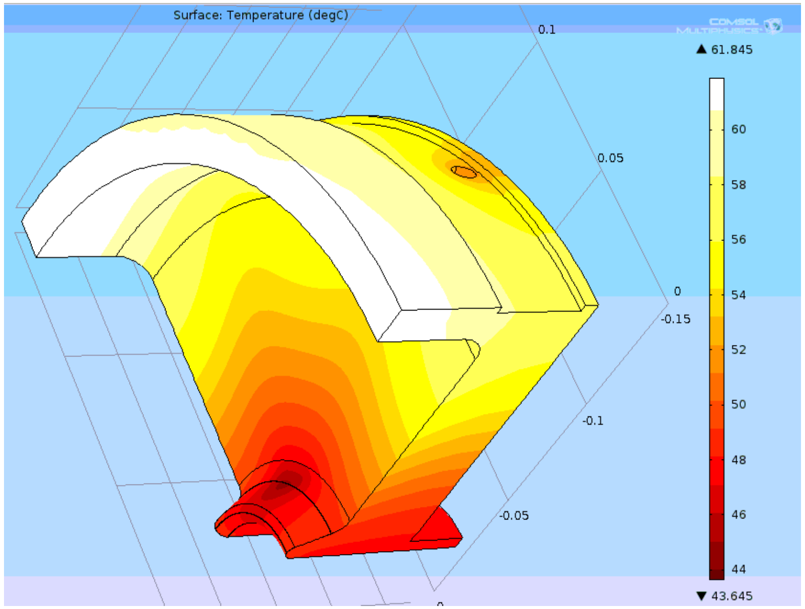
3D as revolution. An idea of how cavity would look like and a preliminary concept for cooling

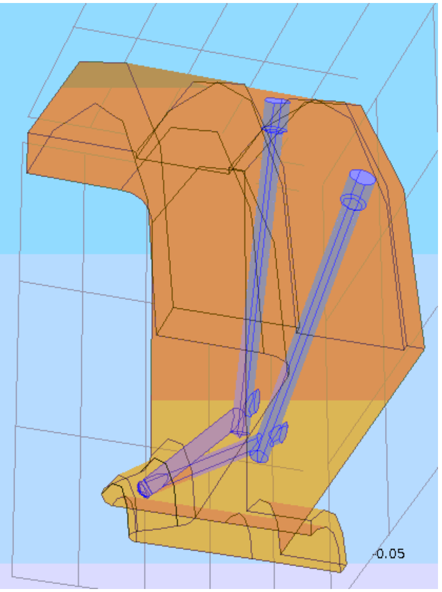


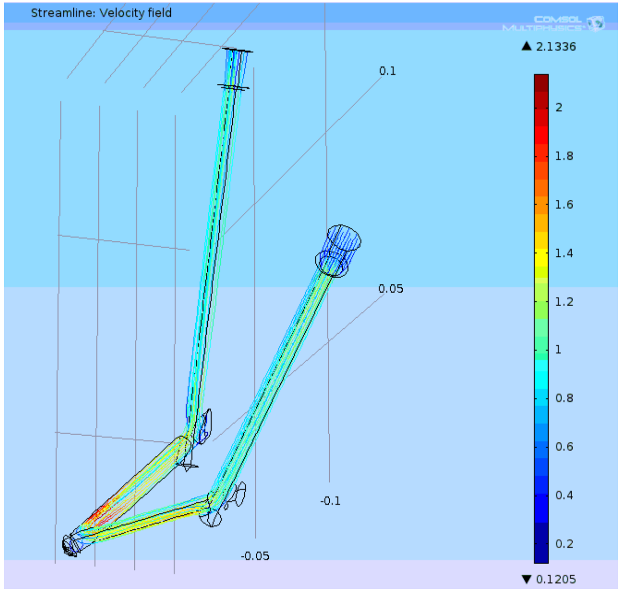






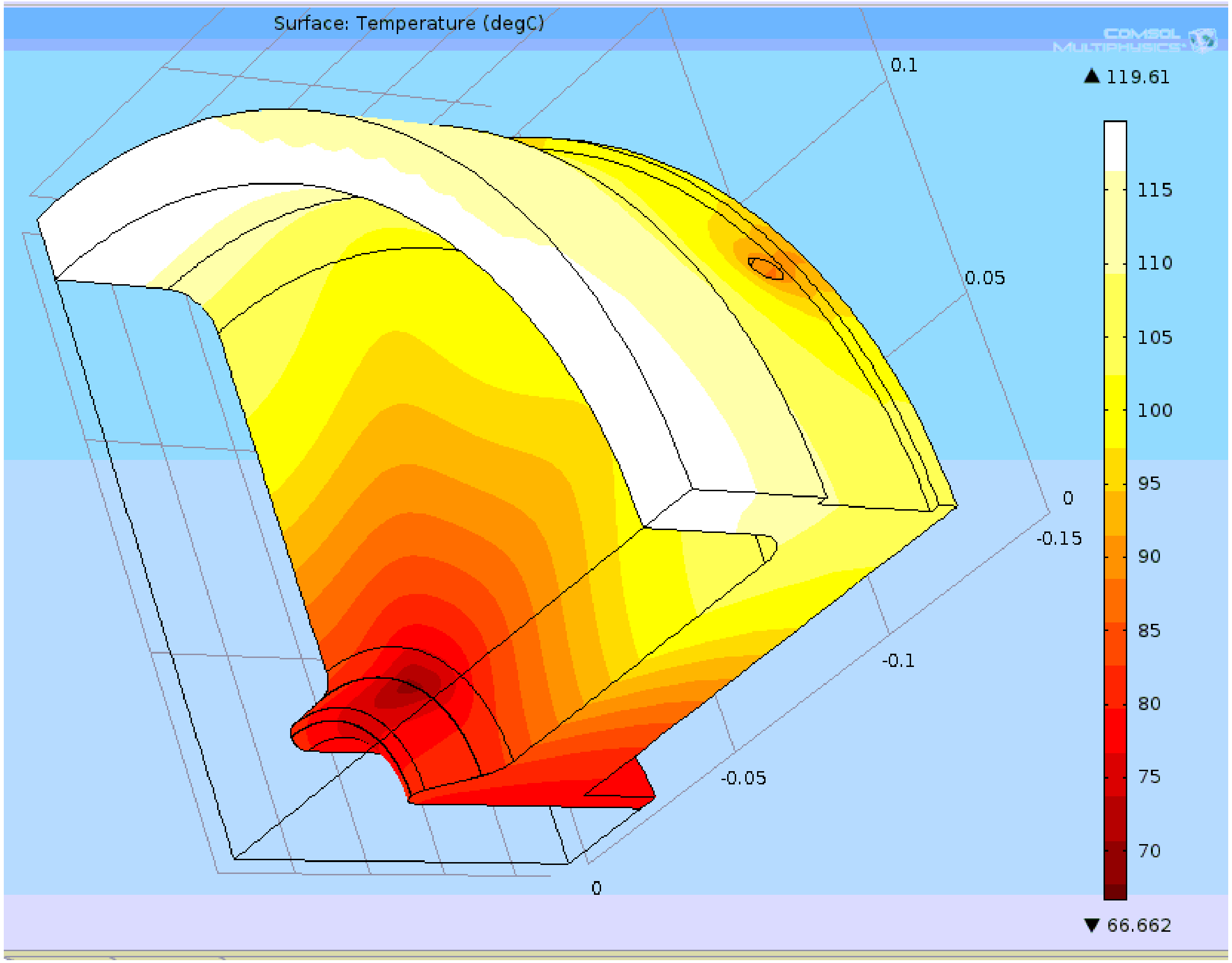




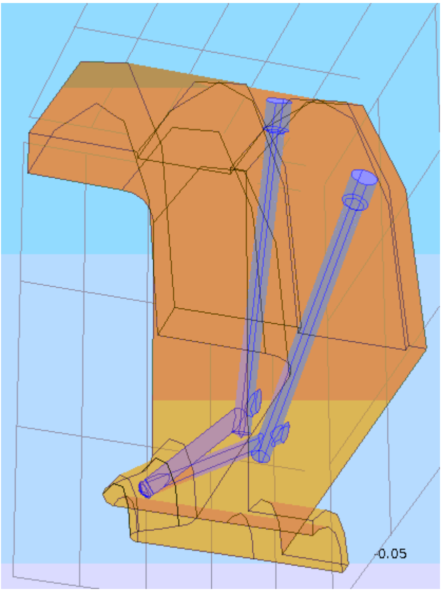


PERLE buncher pre design

Simulation at CW, gradient=1.4 MV/m. Q0=22000, Ploss=8.5 kW total.
Cavity cone angle probably will be >=45 deg to fit the cooling channel

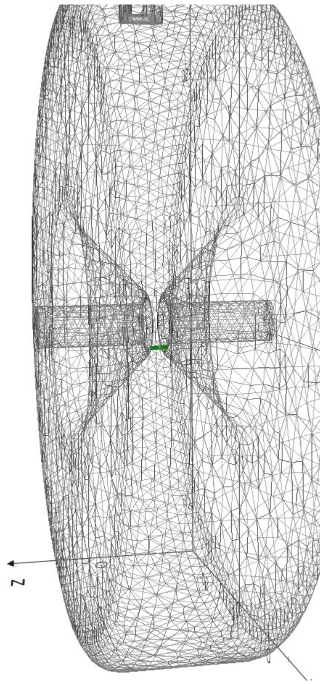


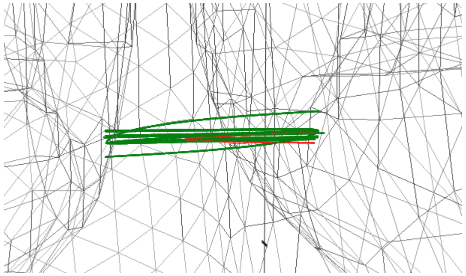
Cooling water:
u = 1.3 m/s
D = 5.5 mm
h = 7100 W/m2K



PERLE buncher

- Additional results to be included during next weeks:
- Beam dynamics preliminary results
- Multipacting simulation preliminary results)





<u>Road map from here:</u>

- Detailed specifications
- Interaction with beam dynamics group
- Cavity mechanical design
- …

PERLE buncher

Thank you for your attention!

Juan Luis Muñoz, jlmunoz@essbilbao.org