Accelerating Structure Design for the AREAL THz –IR FEL

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SW or TW structure

- There is no simple answer to this controversy.

- SW Structure reflects a large fraction of the incident RF power back to the power source during the filling time, and therefore, a high power isolator or a 3db hybrid are needed to absorb the reflected power. In case of TW- only load.

- The fabrication cost of a SW structure is at least 20% higher

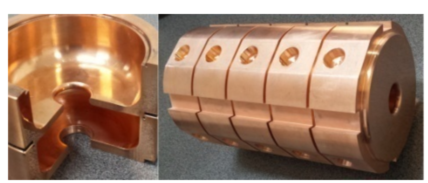
- Of course in SW structures it is possible to achieve higher gradient, but we assume that the structure will be produced in our premises and the tuning will be done by us as well. In our case of more than 46 cups and short filling time the TW structure is preferable.

TW structure decided

- TW structure is easier to produce and tune. For the start it was decided to produce a constant gradient, having similar, easy-to-produce option.
- For energy saving it is decided to have a shorter RF pulse (~ 2 us).
- No need for a high power isolator or a 3db hybrid
- The performed simulations showed that the constant impedance structure is only 1% less compared to constant gradient structure.
- In case of successful production it is possible to review the case of 0.5 m SW structures which will give us the opportunity to have a higher accelerating gradient.

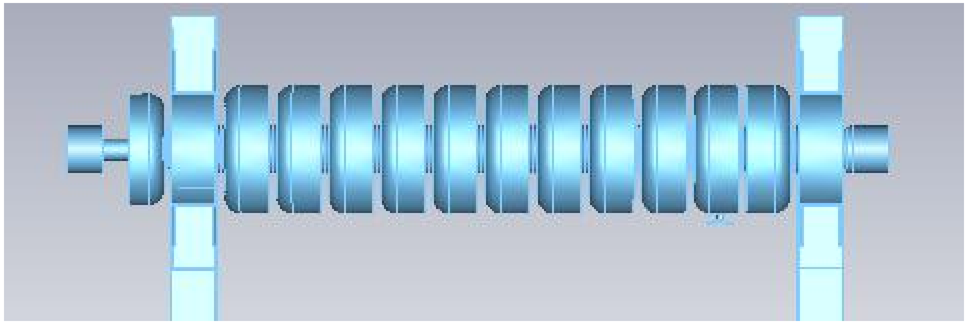
Preliminary Work 2015-2016

- Final design of ACC-s is presented October 2016
- The mechanical design was made by CANDLE engineering, cooling and vacuum groups
- uTCA is implemented (LIBERA is reserved for a back-up)
- Two soldering stations are established
  1. For soldering cups - up to 1 m long pieces
  2. For soldering Cups assemblies and Couplers (up to 4 m)
- Workshops are equipped with modern machining tools.
- Simplified prototype is constructed and tested (without couplers)

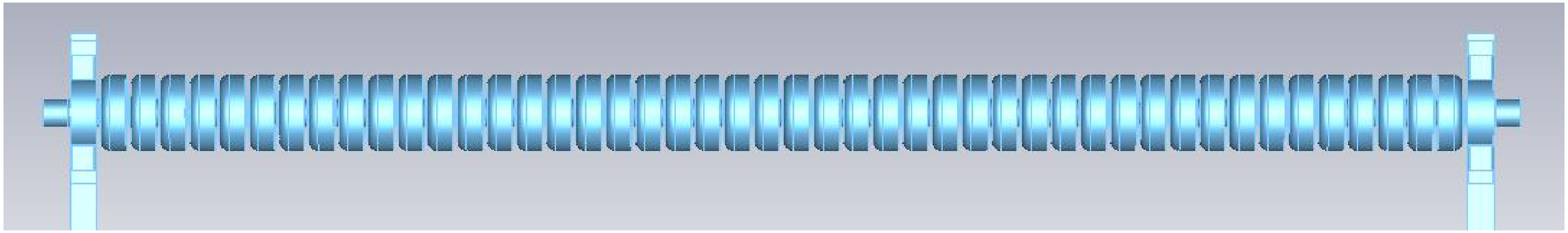


Simulations

As a starting point was S-band hybrid buncher
(for injector upgrade of LINAC II at DESY)

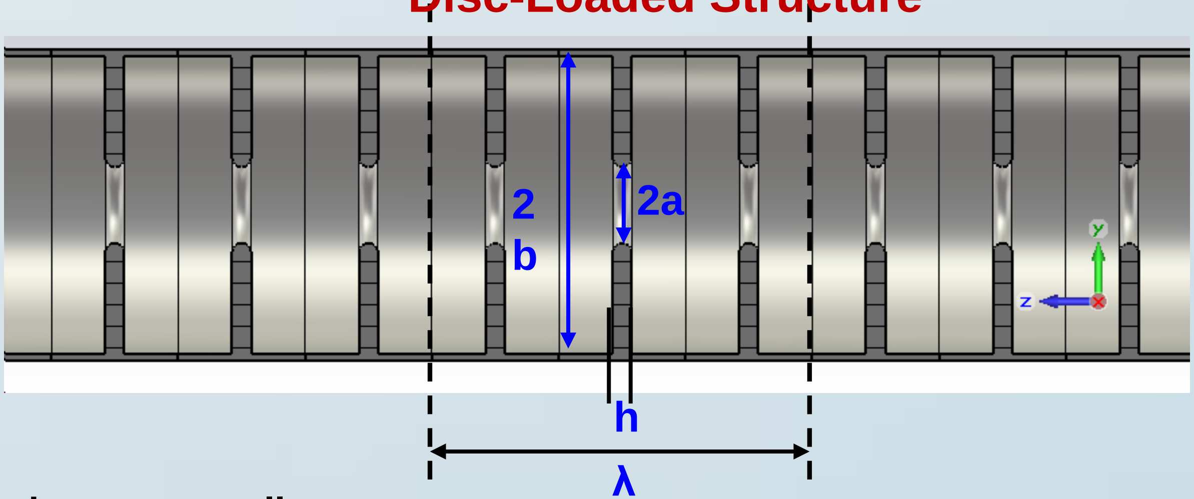


We simply eliminate the SW cell and increase the TW cell numbers up to 46



Introduction

Disc-Loaded Structure



ψ - **Phase advance per cell**

$$\psi \equiv k_z\, L_{cell}$$

α – **Attenuation per unit length**

$$\alpha = \frac{\omega}{2Q} \cdot \frac{1}{V_g}$$

Phase & Group Velocities

$$\frac{\omega}{c} = \frac{2.405}{b}\sqrt{1+\chi\,(1-\cos(\psi)\,e^{-\alpha h})}$$

$$\frac{V_\varphi}{c} \equiv \frac{\omega / c}{k_z} = \frac{2.405\,L_{cell}}{b\,\psi}\sqrt{1+\chi\,(1-\cos(\psi)\,e^{-\alpha h})}$$

$$\frac{V_g}{c} \equiv \frac{d\omega / c}{dk_z} = \frac{2.405^2}{3\,\pi^2\,J_1^2(2.405)}\,\frac{\lambda\,a^3}{b^4}\,e^{-\alpha h}\,\sin(\psi)$$

$$\chi \equiv \frac{4\,a^3}{3\,\pi\,J_1^2(2.405)\,b^2\,L_{cell}} << 1$$

- Phase velocity is mainly influenced by ***b*** and ***ψ/L***
- Group velocity is sensitive to ***a*** and ***b.***

- The synchronous phase velocity $V_\varphi = \beta\, c$ is adjusted by ***b.***
- The group velocity is defined by ***a.***

Traveling Wave Cavities & Beam Interaction

Constant Impedance (CZ)

$\alpha = const$

$$\tau = \alpha L = \frac{\omega L}{2QV_g}$$

$$V_{max} = \sqrt{\frac{2}{\tau}\left(1-e^{-\tau}\right)} \cdot \sqrt{r_s L P}$$

Constant Gradient (CG)

$\alpha \neq const$

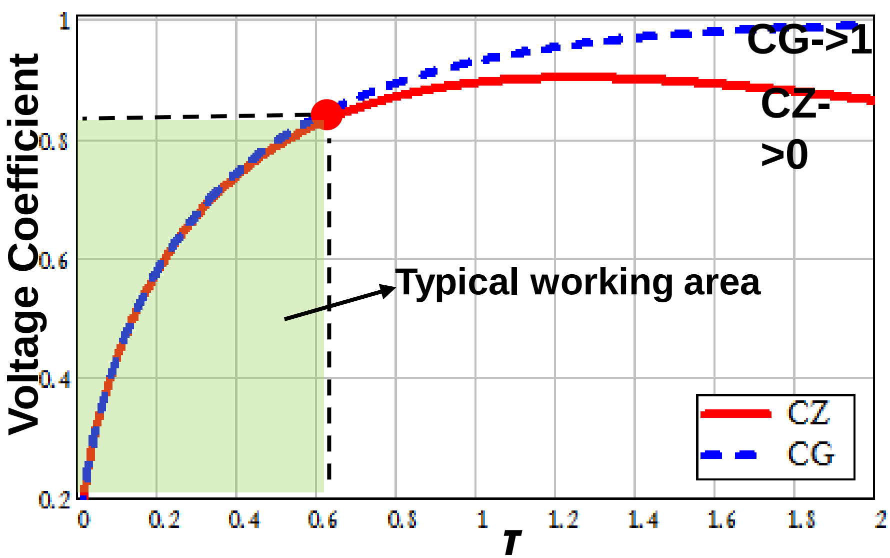
$$\tau = \int_0^L \alpha(z)\,dz$$

$$V_{max} = \sqrt{\left(1-e^{-2\tau}\right)} \cdot \sqrt{r_s L P}$$

- RF to Beam energy transfer strongly depends on V_g .
- To increase efficiency => decrease V_g => decrease gap radius.
- Smallest realistic gap radius ~ 1cm.

Voltage Coefficient

Assume same $r_s L$ for CZ and CG structures



Parameters for L~1.4m, 2π/3 CZ-TW Structure

R_{gap} [mm]	V_g/c [%]	τ	Filling time $t_f=L/V_g$ [μs]
14	~2,82	~0.11	~0.165
12	~1.64	~0.19	~0.284
10	~0.82	~0.38	~0.570

SLAC CG-Cavity L=3m:
R_g=13-10mm, τ~0.57

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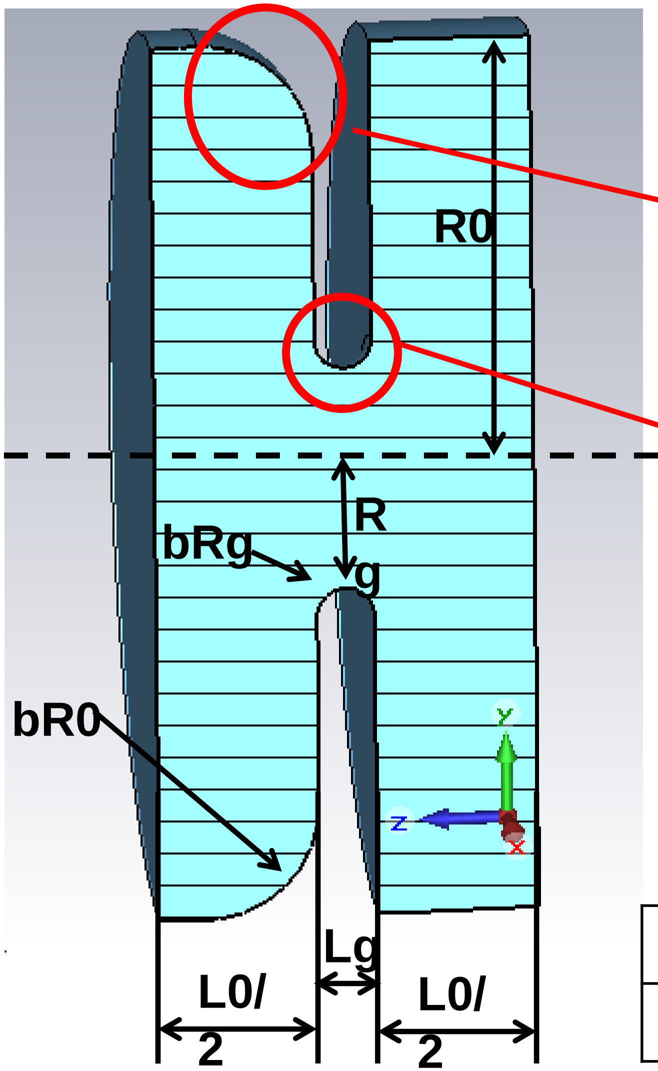
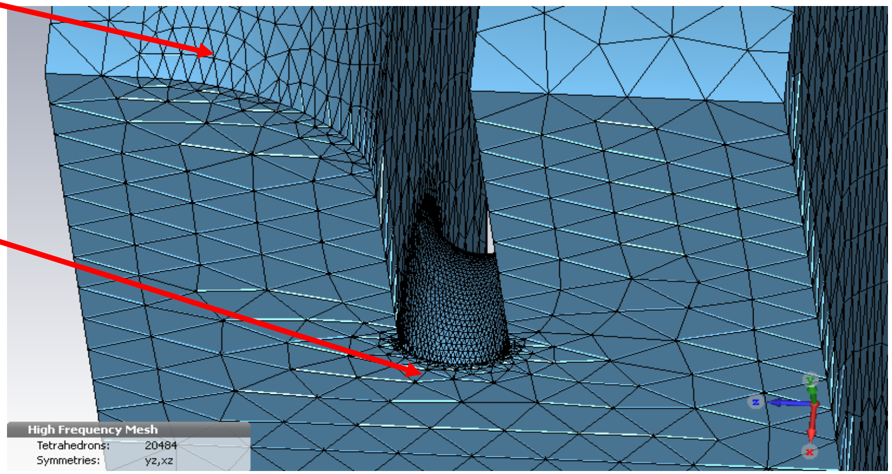
Periodic 2π/3 Cell Design

Geometry & Mesh



- Blended parts require careful meshing!
- Tetrahedral mesh – with curved elements.



Geometry Parameters for freq. ~ 2.9979 GHz

Lcell = 33.325 mm~ λ/3

Lg [mm]	Rg [mm]	bRg [mm]	L0 [mm]	R0 [mm]	bR0 [mm]
5.0	10.0	2.5	28.325	39.8127	10.0

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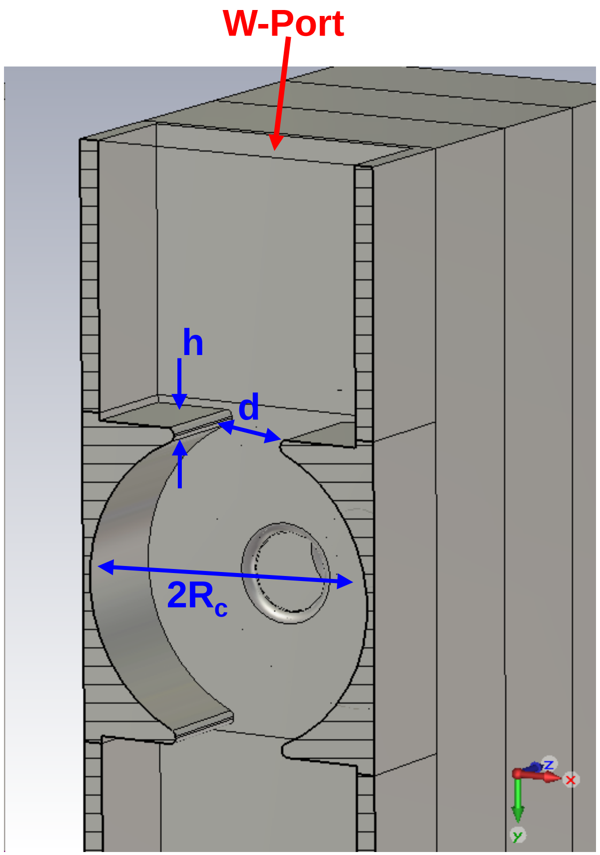
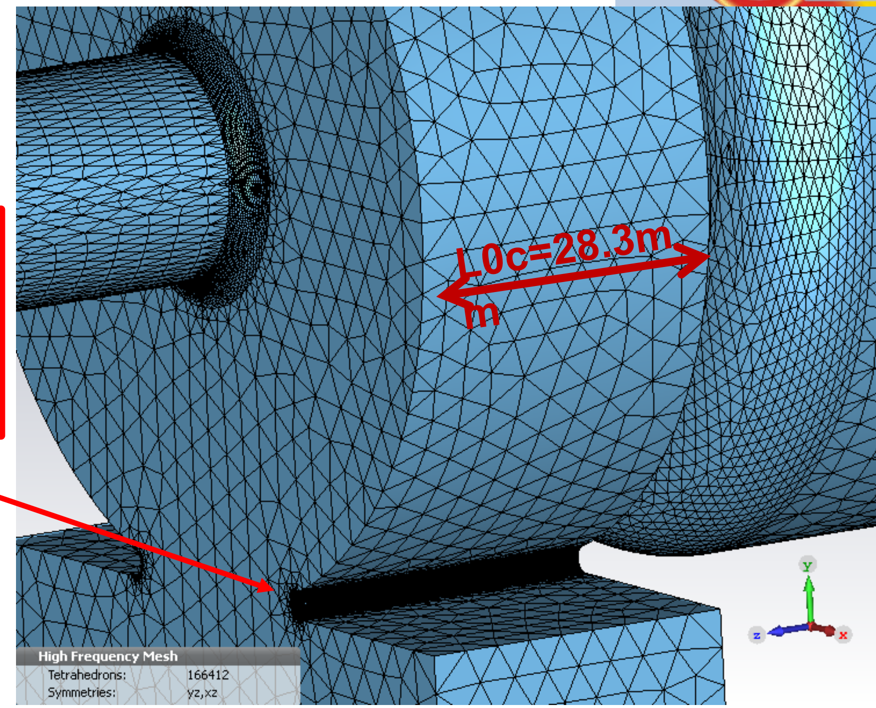
The Design of Couplers& Reduced Model

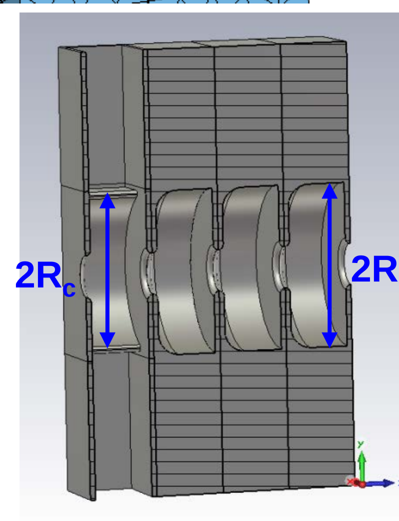
Geometry & Mesh



Critical points are coupler hall blending's ~1.15mm

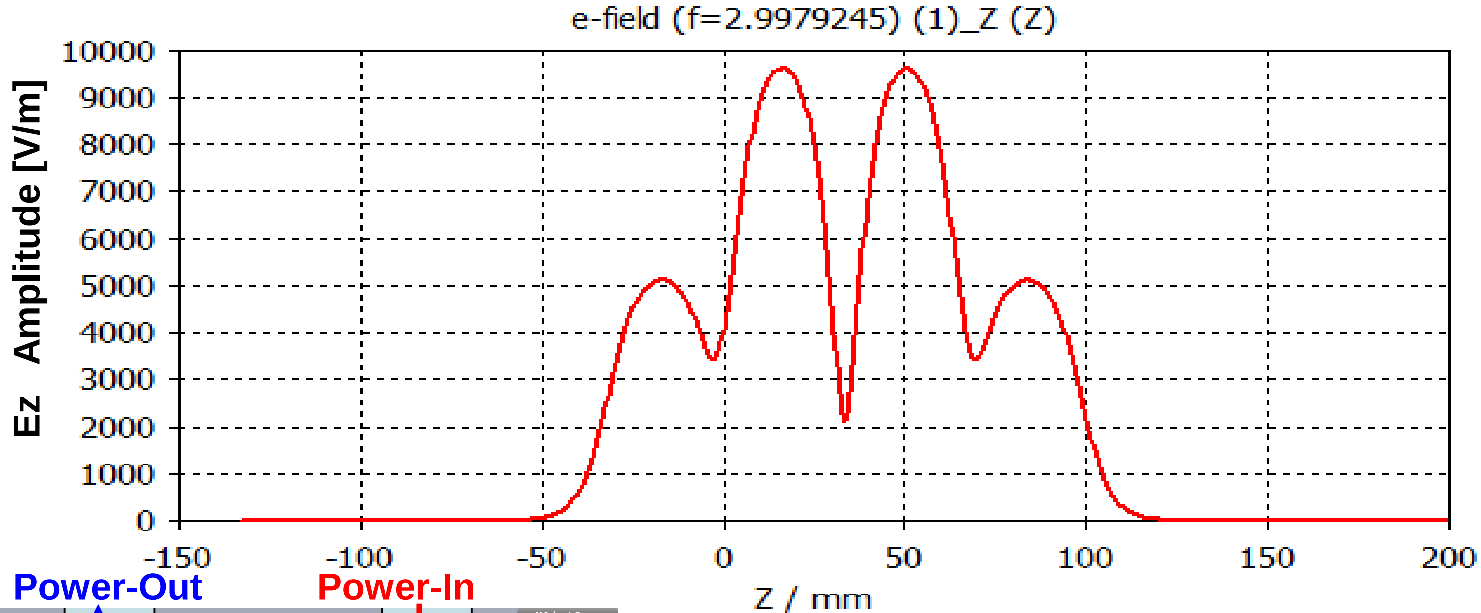


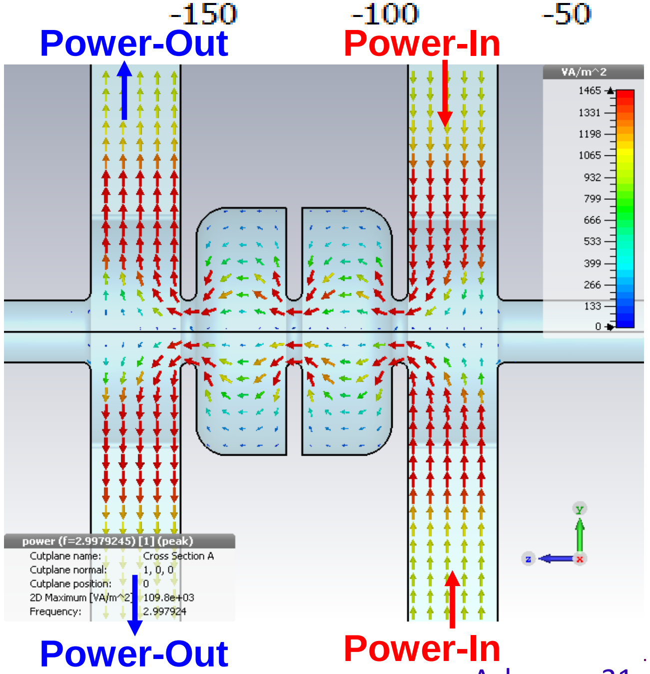
- Coupler is optimization for 2,9979 GHz 2π/3 TW mode.
- The resonant frequency is sensitive on **Rc** & **d** and has very weak dependency on **h.**
- h=2mm is fixed & for every coupler hall opening **d** the frequency is tuned by **Rc. =>** **For Rg=10mm ,the optimal parameters are d=25mm => R0c=37.8332mm.**
- **Ing- & Out-going beamppe radiuses are 10mm & the cells in between couplers are the exact copies of periodic cell.**

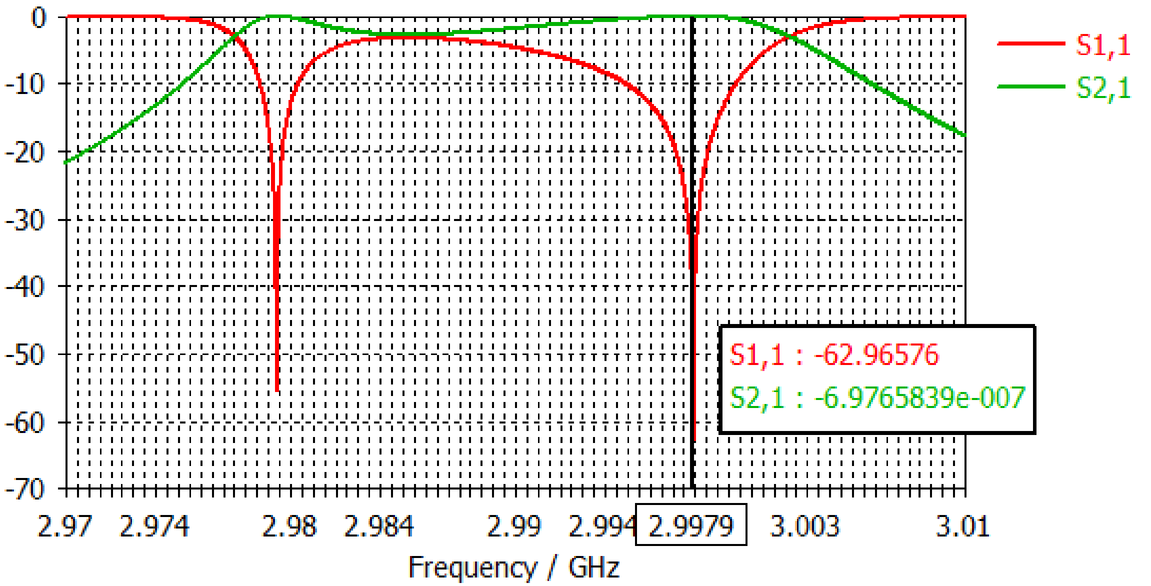


The Design of Couplers& Reduced Model

Coupler design step1 : Optimization with full symmetry (Dual Feed)

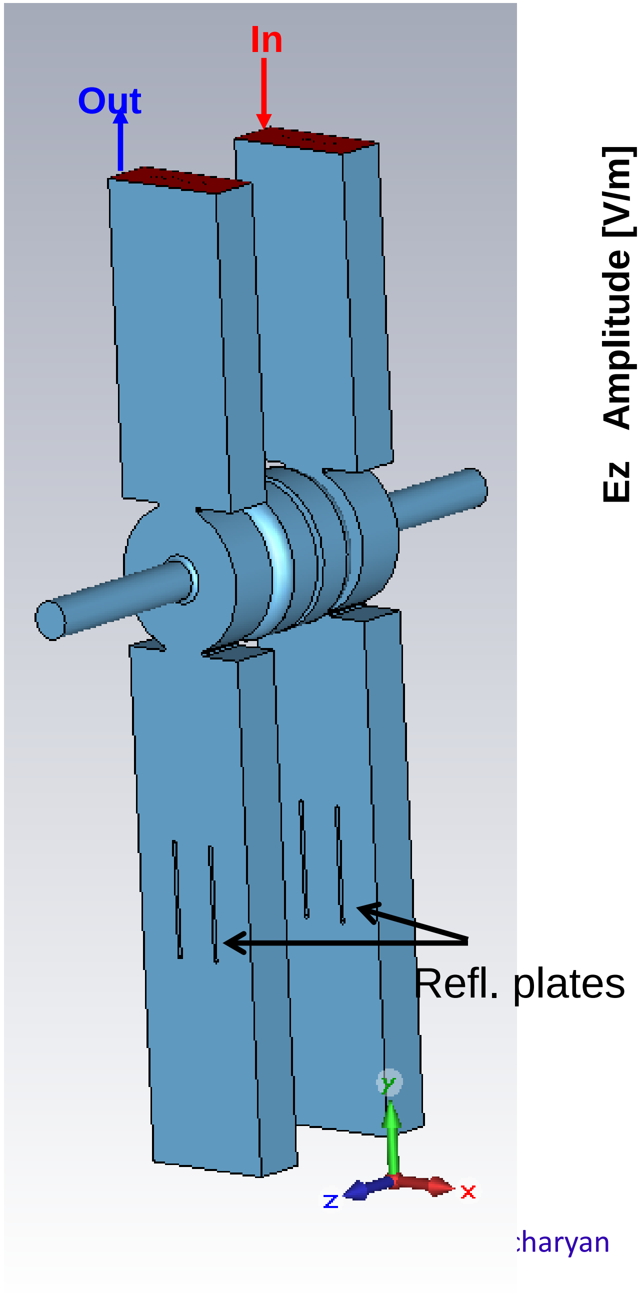


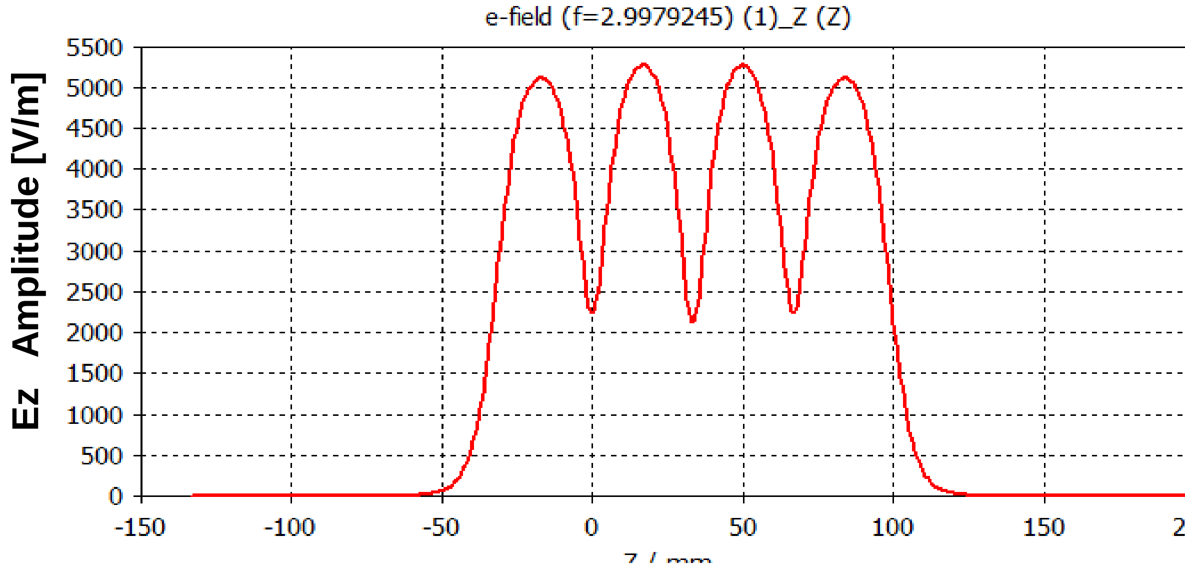


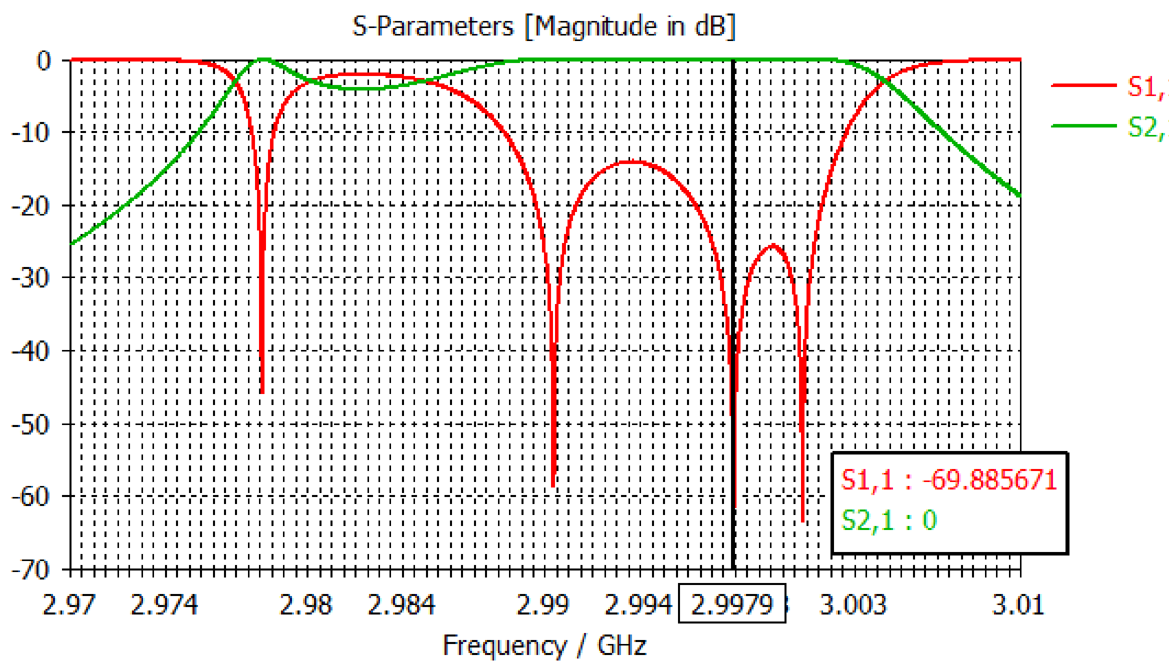


The Design of Couplers& Reduced Model

Coupler design step 2 : Adding Reflector plates & position







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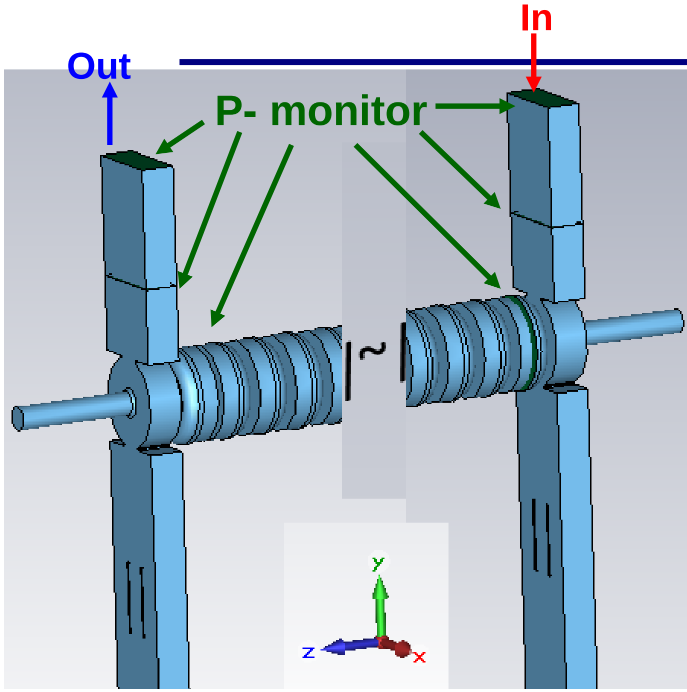
46 cell TW cavity



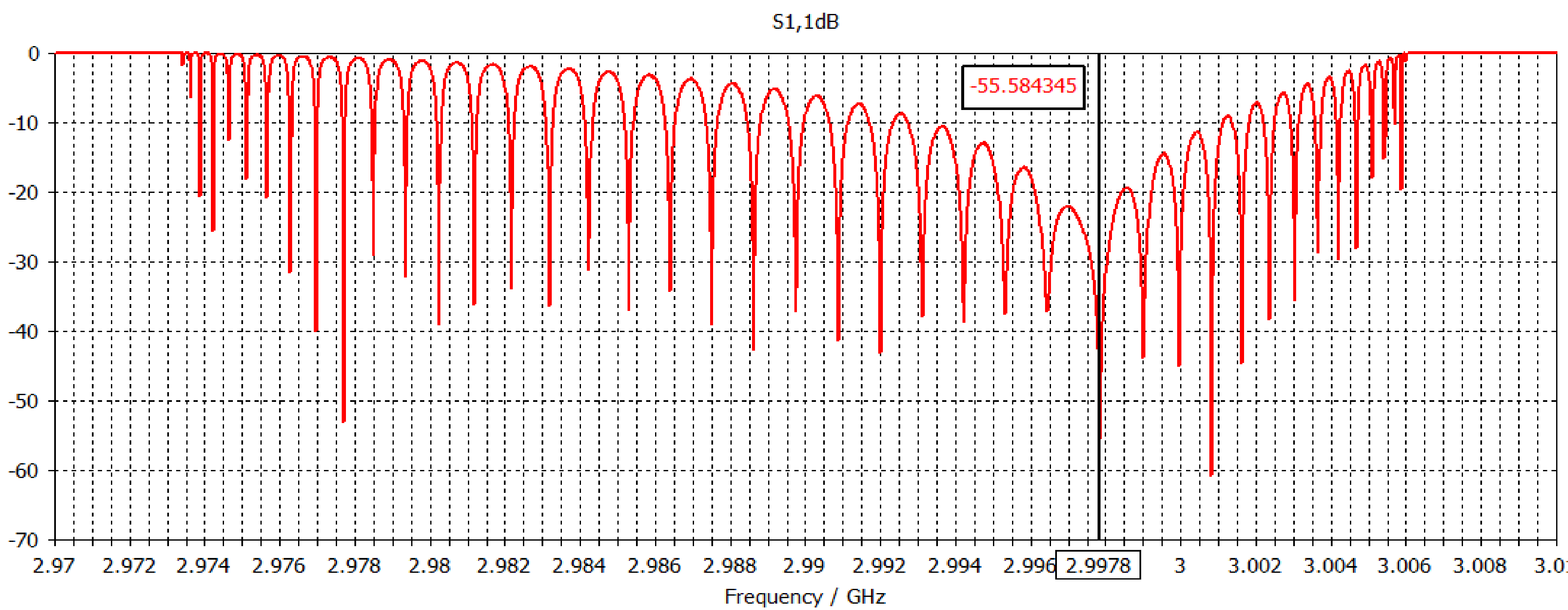
PEC Boundary

Final Step: Add periodic cells (no additional tuning)

$$\left.\begin{array}{l}\text{No. periodic cells} = 42\\ \text{No. cells of reduced model} = 4\end{array}\right\} 46 cells \Rightarrow Leff \sim 1.53m$$

$$\text{min. length of each beampipe} = 5cm \Rightarrow L_{total} \geq 1.64m$$

- The power flow is checked to be 1 Watt at each monitor.



46 cell TW cavity

Constant Impedance (CZ)

$$\tau = \alpha_0 L = \frac{\omega L}{2QV_g} \quad , \quad V_{max} = \sqrt{\frac{2}{\tau}\left(1-e^{-\tau}\right)} \cdot \sqrt{r_s L P} = C_V \cdot \sqrt{r_s L P}, \quad C_V \equiv \sqrt{\frac{2}{\tau}\left(1-e^{-\tau}\right)}$$

Boundary-PEC

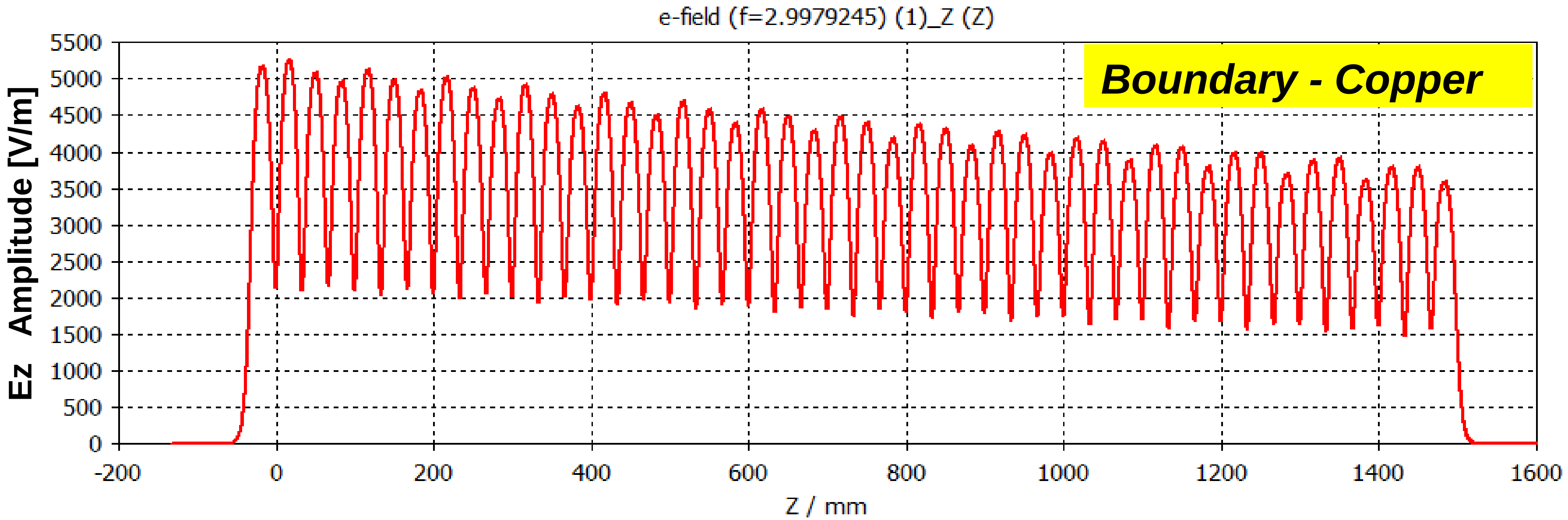
$$\left.\begin{array}{l} P_{simulated} = 1 Watt \\ Q \sim 14070 \\ freq. \sim 2.99785 \\ L_{eff} = 1.5m \\ V_{max} \sim 5.9\,kV \\ V_g / c \sim 0.989\% \\ \alpha_0 \sim 0.225 m^{-1} \end{array}\right\} \Rightarrow \begin{cases} \tau = \alpha_0 \cdot L_{eff} \sim 0.3388 \\ C_V \sim 0.6975 \\ r_s = V_{max}^2 / C_V^2 / L_{eff} \sim 47 M\Omega / m \end{cases}$$

From single cell simulation

Boundary-Copper

$$\left.\begin{array}{l} P_{simulated} = 1 Watt \\ freq. \sim 2.99785 \\ L_{eff} = 1.5m \\ V_{max} = 4.94\,kV \\ \tau \sim 0.335 \\ \alpha_0 \sim 0.231 m^{-1} \end{array}\right\} \Rightarrow \begin{cases} C_V \sim 0.7055 \\ r_s \sim 32.7\, M\Omega / m \end{cases}$$

From Power monitors:



Summary & Discussion

Final Parameters

$freq. \sim 2.99785$
$L_{eff} = 1.5m$
$L_{tot} \geq 1.64m$
$\tau \sim 0.335$
$\alpha_0 \sim 0.231 m^{-1}$
$C_V \sim 0.7055$
$r_s \sim 32.7\, M\Omega / m$

In-Out Waveguide Dimensions [mm]: 72 x 28.3

$P_{out} = P_{in} e^{-2\tau} \sim 0.4972\, P_{in} \to \sim 50\%$
$V[MeV] \sim 4.942 \cdot \sqrt{P[MW]}$

$P = 20MW \to \sim 22\, MeV$
$P = 40MW \to \sim 31\, MeV$

- Cross check with T-Solver is very time consuming: The modeling of small blendings requires very dense Hexahedral mesh. As possible simplification could be the removal of blending's of Coupler hall & Reflector Plates => Tune of res. frequency from the beginning.
- Simulation with **Lossy Boundary** seems to be more realistic & gives directly all required cavity parameters: Voltage power coefficient, attenuation -> shunt impedance can be estimated.
- Waveguides are taken long to exclude evanescent modes at acc. res. freq..

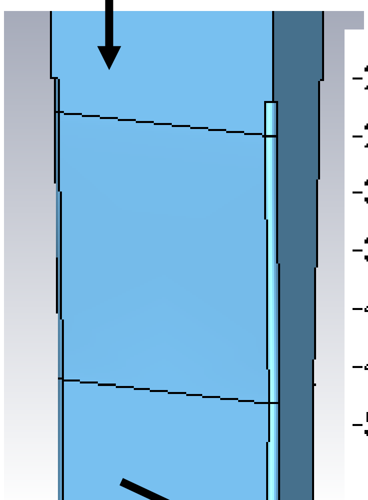
Design II - Modified Couplers Waveguides

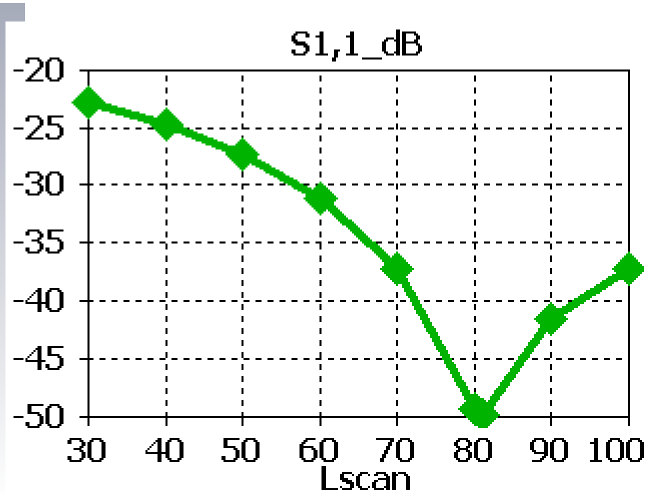
Optimized design
Input Coupler WG- 72x28.3mm

Modification
Input Coupler **WG- 72x34mm**

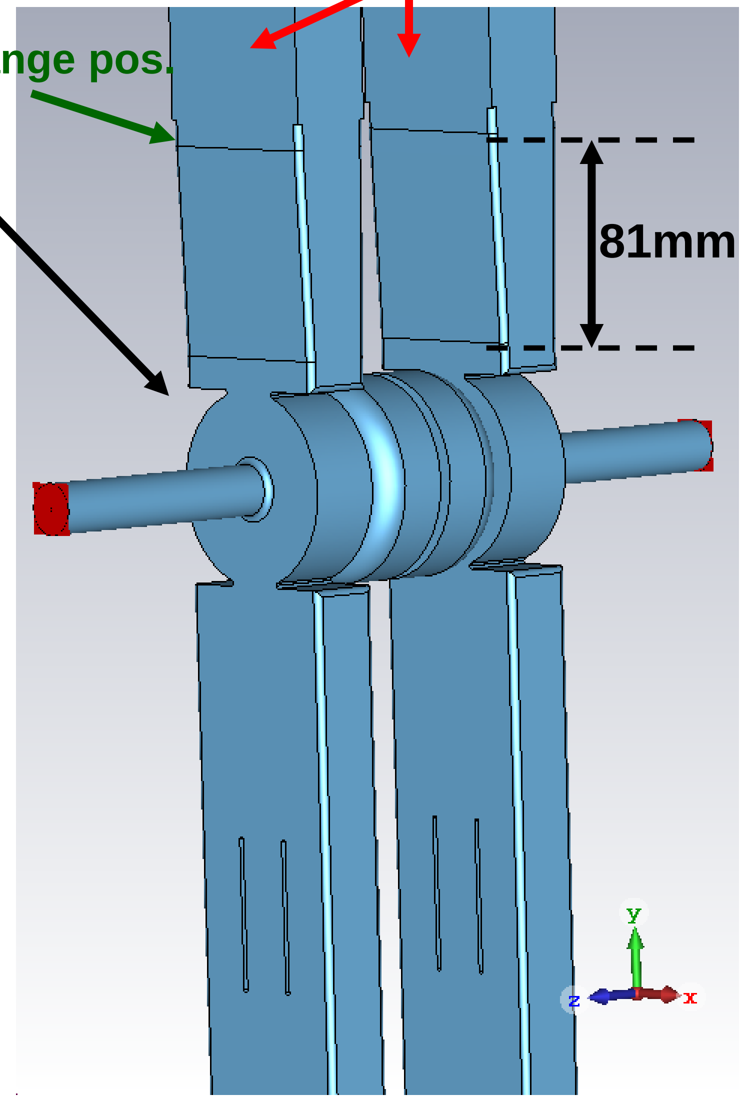
- Taper WG 72x28.3_34mm, Optimum (Low reflection) L=81mm
- WG corner blending radius 2.5mm
- The tuning to resonance frequency is performed only by position tuning of reflector plates.

Input Port (WG 72x34mm)



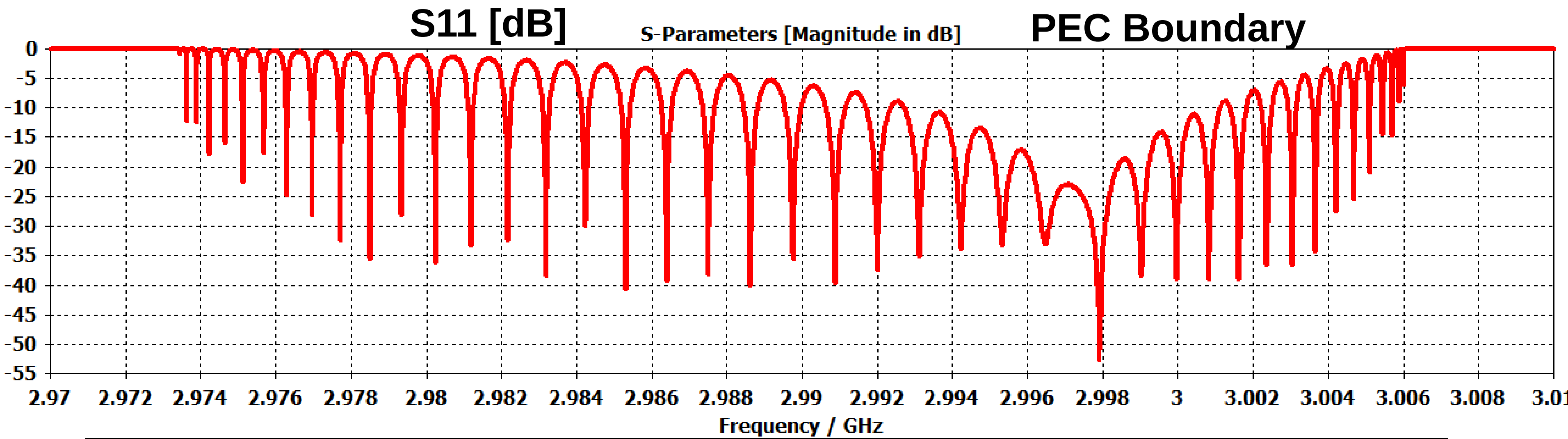


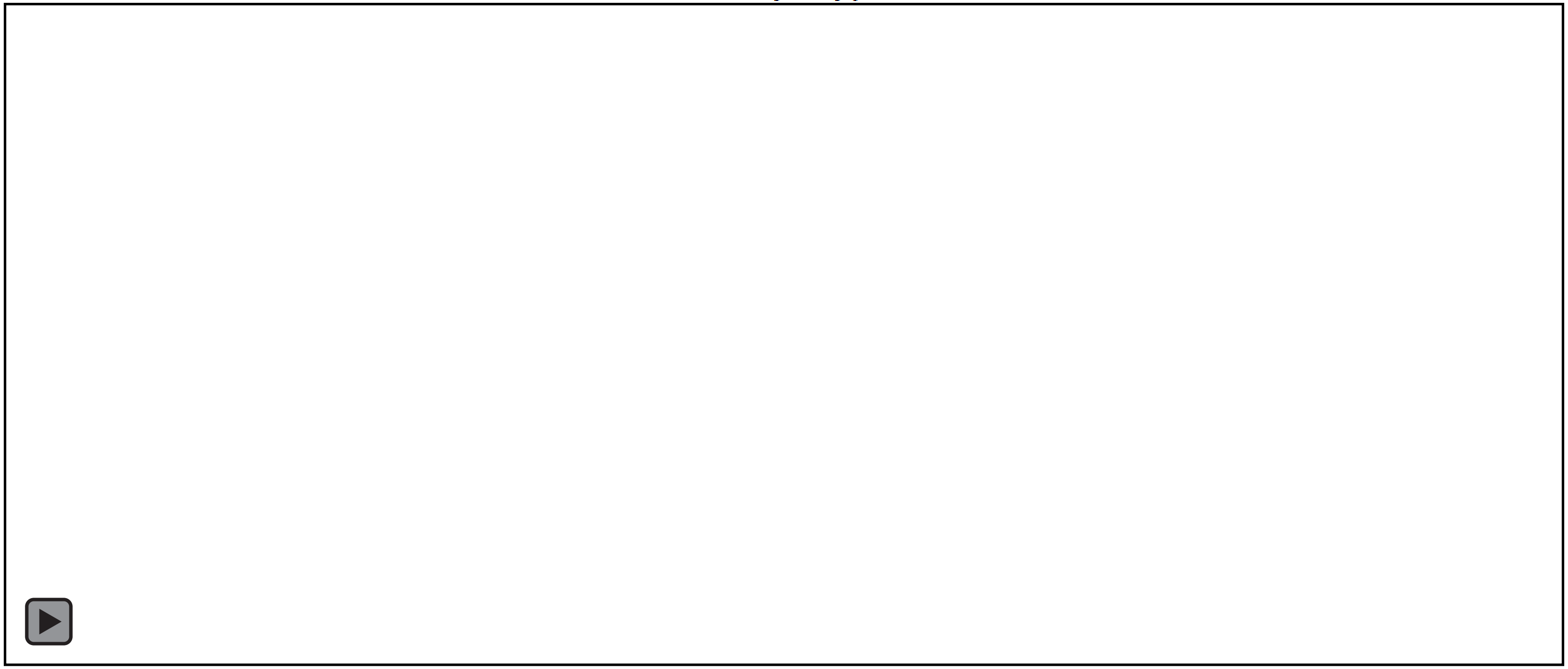
Output Port (WG 72x28.3mm)



Courtesy of A. Tsakanian

Design II - Modified Couplers Waveguides



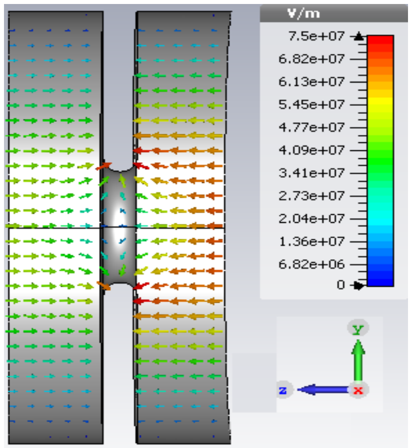


Periodic 2π/3 Cell Design

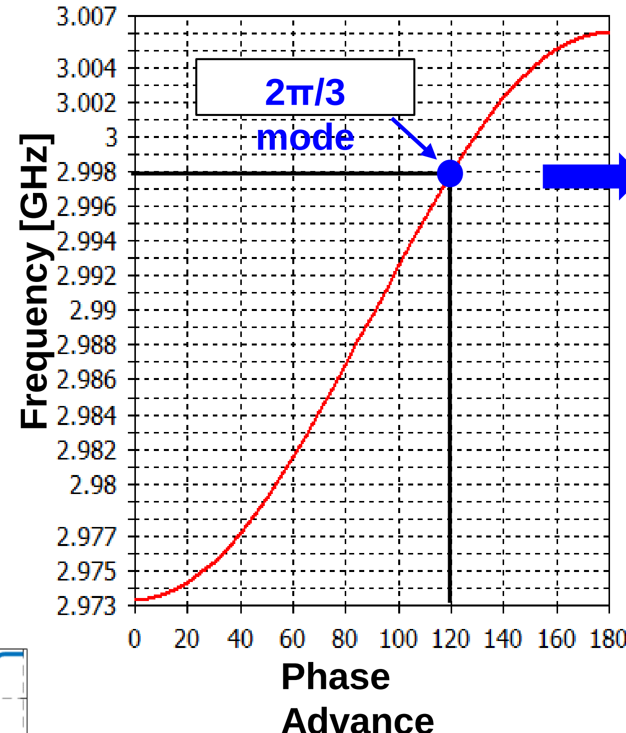
CST
COMPUTER SIMULATION TECHNOLOGY

E-Solver with periodic BC

- Phase advance 120^0
- Complex mode-> $E(\omega t=90^0)\neq 0$ Expected for Traveling Wave.

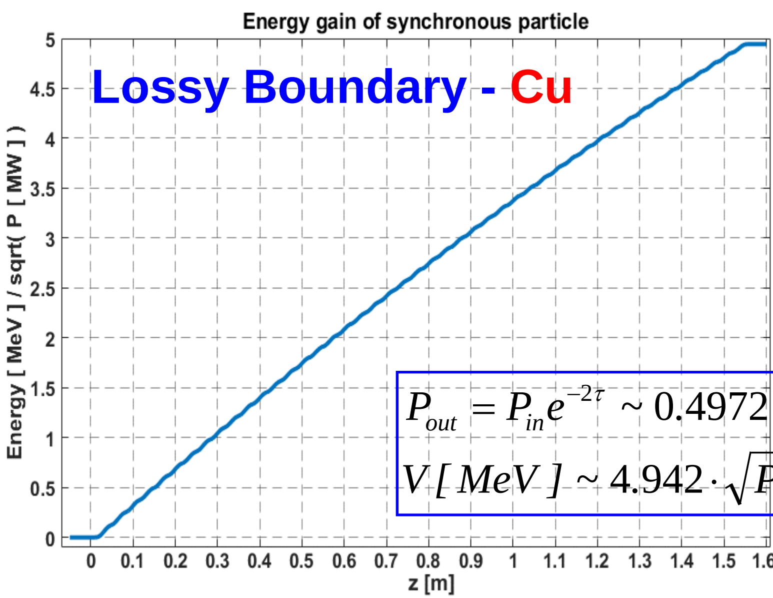


Single Cell Phase Scan



- $V_\phi = c$
- $V_g/c \sim 0.82\%$

From slope

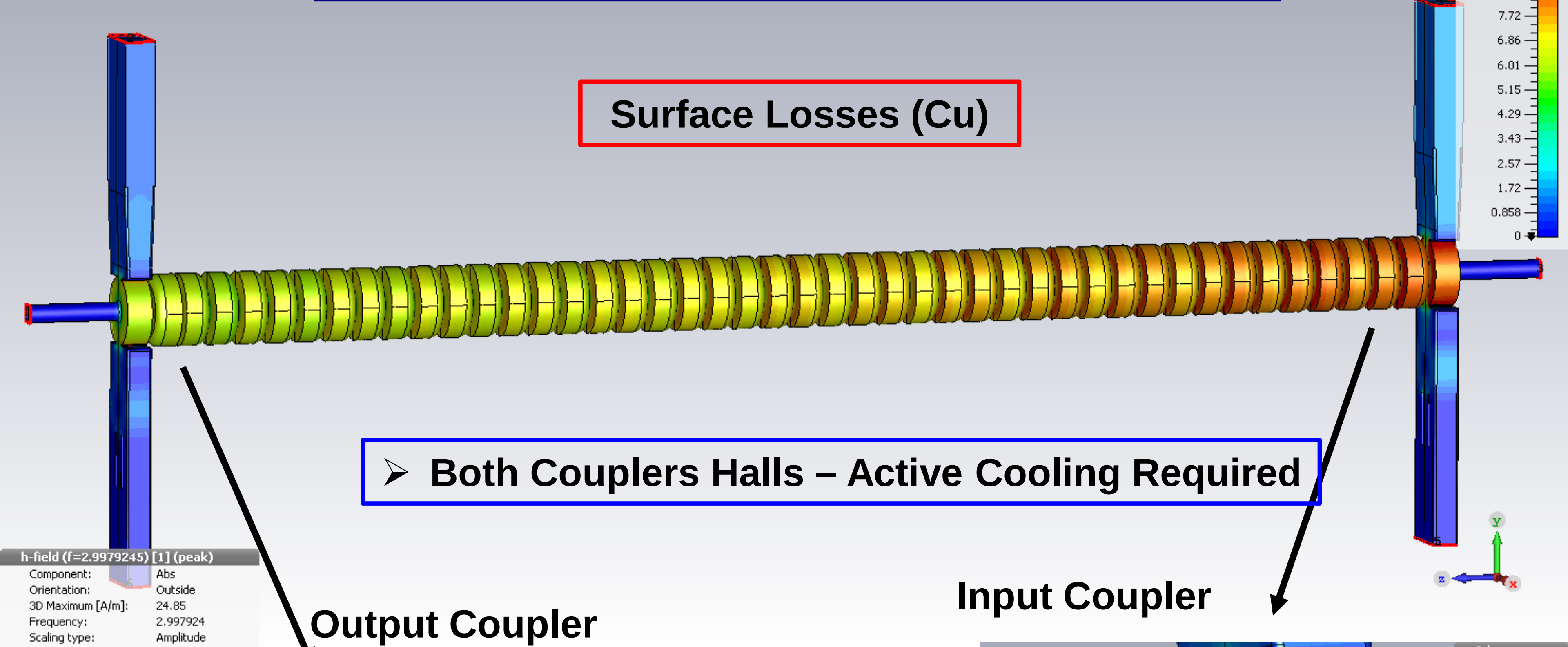


$$P_{out} = P_{in} e^{-2\tau} \sim 0.4972 P_{in} \rightarrow \sim 50\%$$

$$V[MeV] \sim 4.942 \cdot \sqrt{P[MW]}$$

- For TW mode the phase advance is important.
- The E field of TW mode should be non-zero at $\omega t=90^0$, while in SW case it is zero.
- Careful with many cell simulation…
  for example in 3-cell case the phase advance becomes 360^0 :
  Simulation gives Real Eigenmodes and the E-field phase plot vs z-direction is not correct=>
  => underestimation of shunt impedance R_s!

Design II - Modified Couplers Waveguides

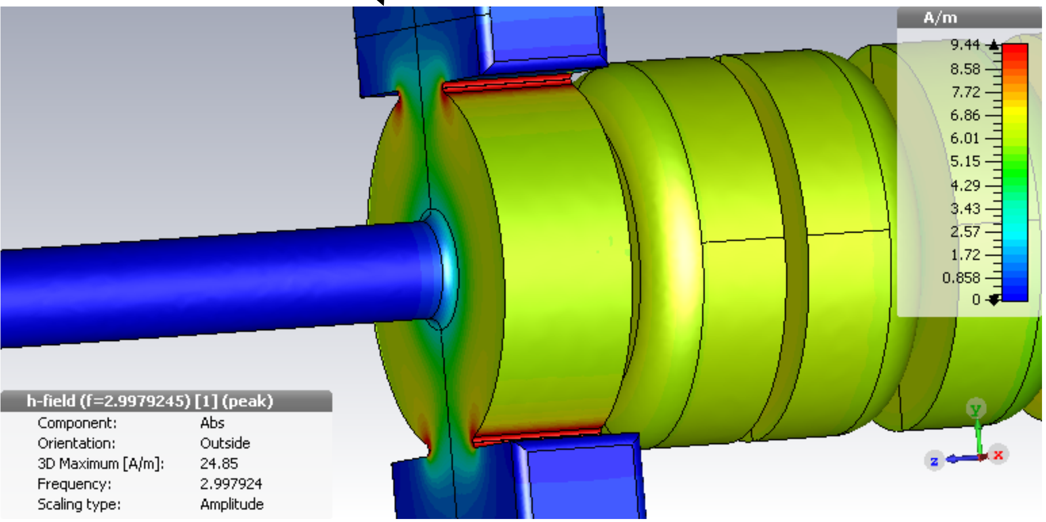


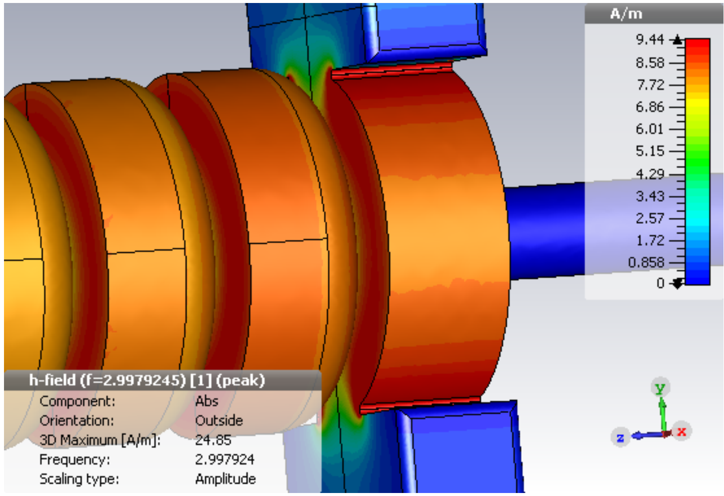
Surface Losses (Cu)

- **Both Couplers Halls – Active Cooling Required**

Input Coupler

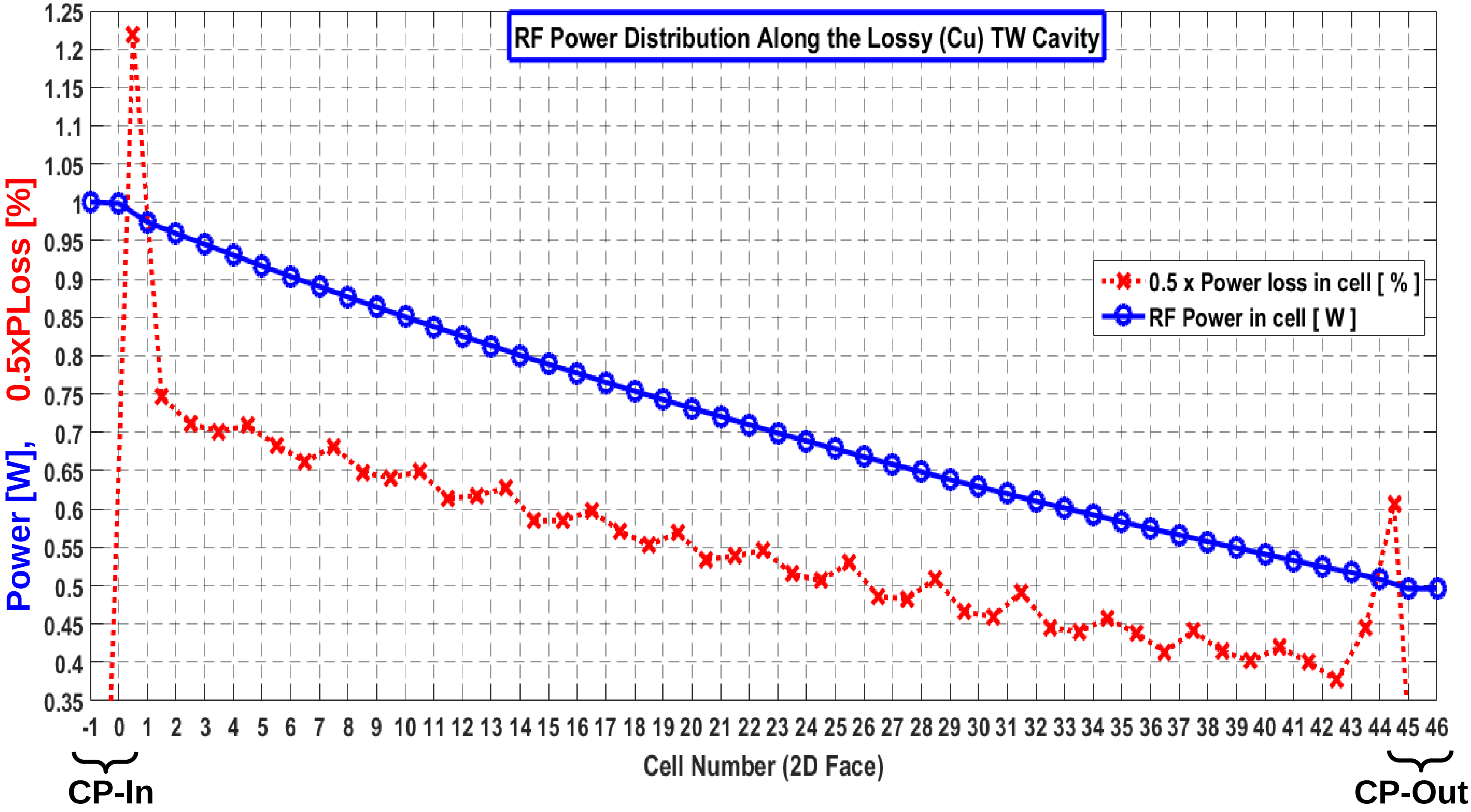
Output Coupler





Design II - Modified Couplers Waveguides

Power evolution & losses along the Cavity



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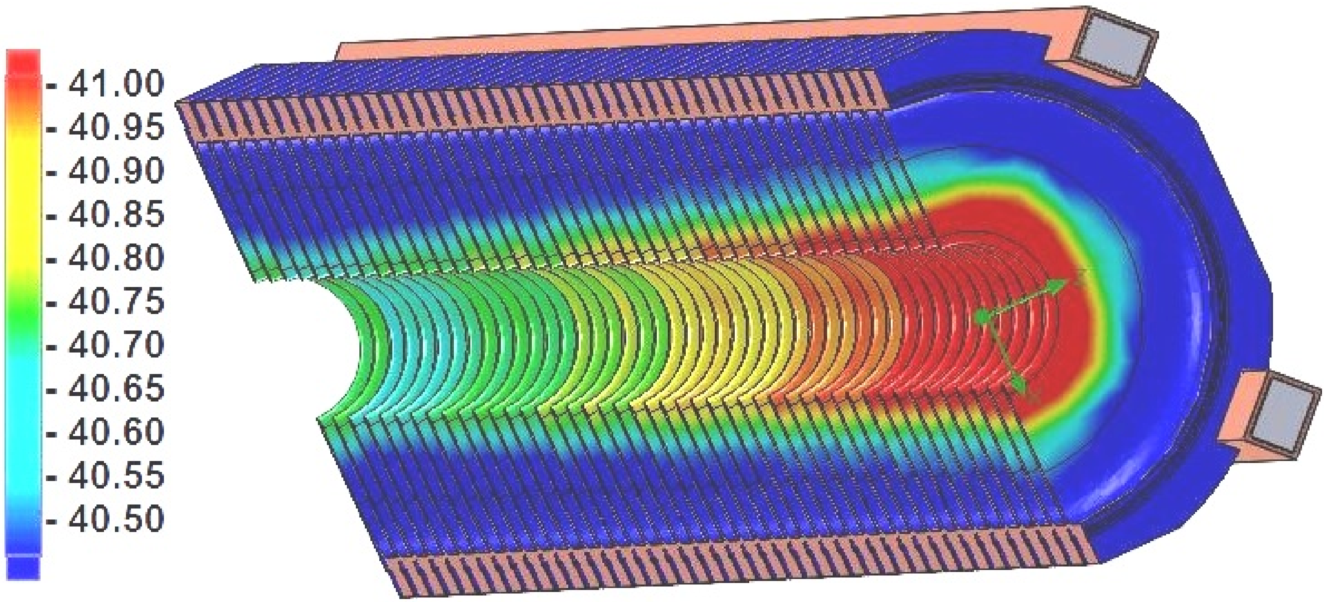
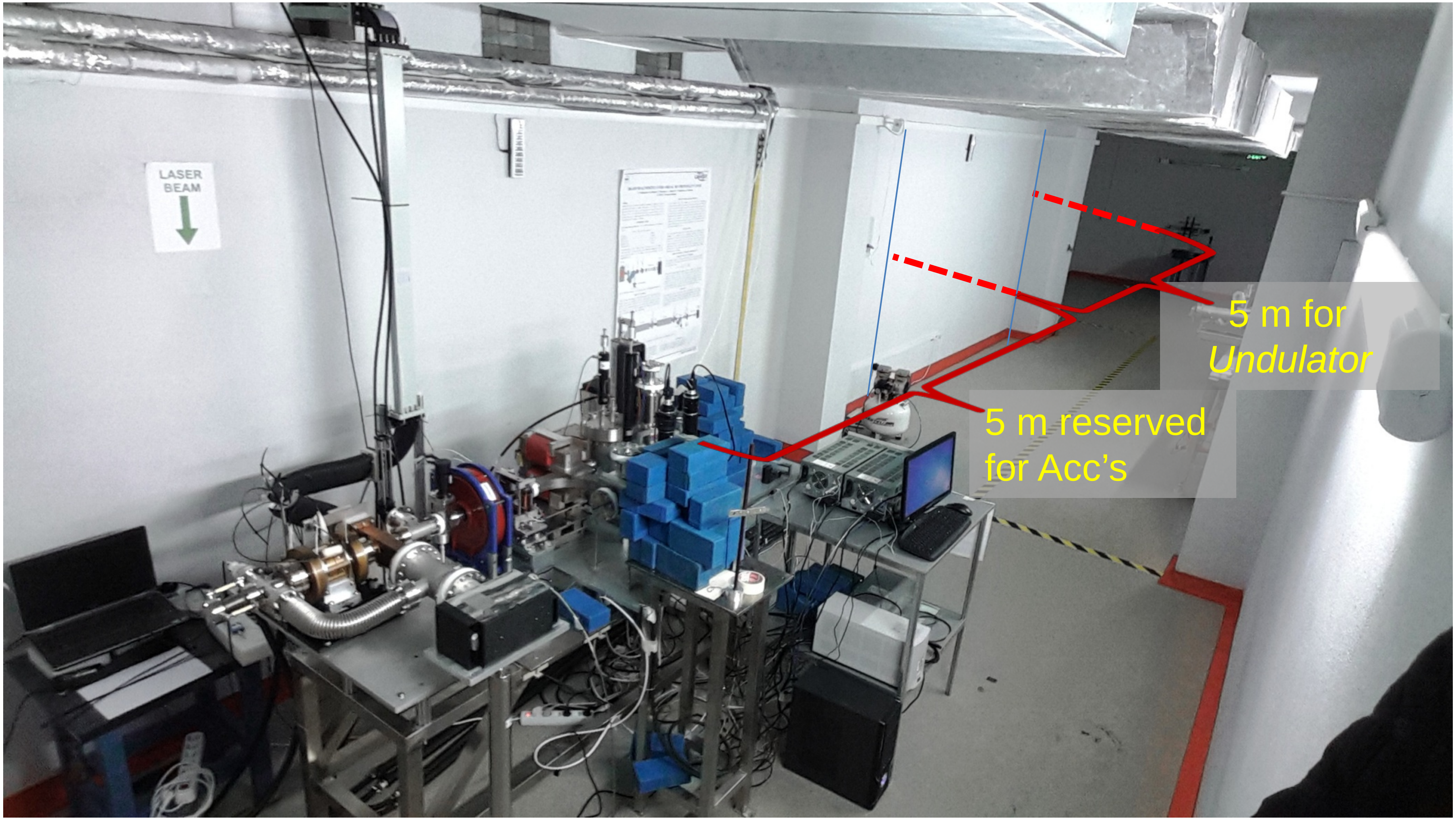
Cooling

Simulations performed for mean 300W input power show that the temperature deviation along the structure will not exceed 0.5^{o}C at 40^{o}C temperature level, for water flow of 20 l/min.



Copper thermal conductivity and outer surface heat loss are taken into account. Additional cooling loops are foreseen for input/output couplers.

Tunnel Layout



RF System Upgrade

- To achieve goal of 50 MeV energy upgrade
- Accelerating section(s)
- The AREAL RF system will consist of 2 RF stations
- Each RF station will have 1 klystron,
  HV modulator, a low-level RF system, preamplifier
  and an interlock and control system

- 1 station - for RF Gun (later on the existing modulator and klystron will be replaced)
- 2nd station – for accelerating section(s) operation
- LLRF systems will be Based on uTCA (implemented)
- RF power 7 MW for Gun and 37 MW for ACCs
- Interlock and control system

Waveguide path

Parallel connection

$V_{acc\ II} = 2*5*\sqrt{P}$

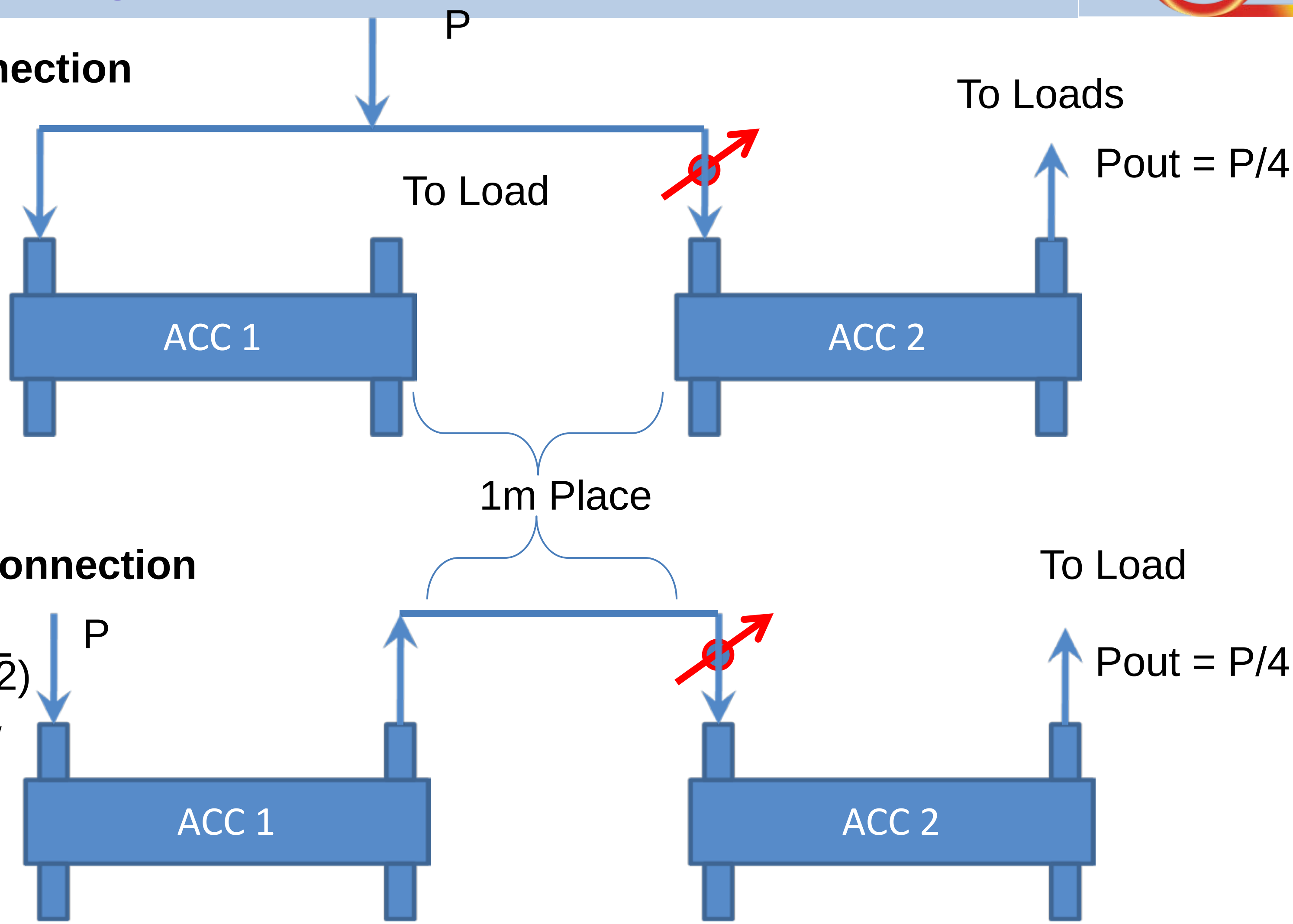
24,5 MeV @6MW

Consequent connection

$V_{acc\ --} = 5*\sqrt{P}(1+\sqrt{2})$

29,5 MeV @ 6MW

$\frac{V_{acc\ --}}{V_{acc\ II}} = \mathbf{1,2}$



With the consequent ACCs one can reach the missing 45 MeV with 30 MW power

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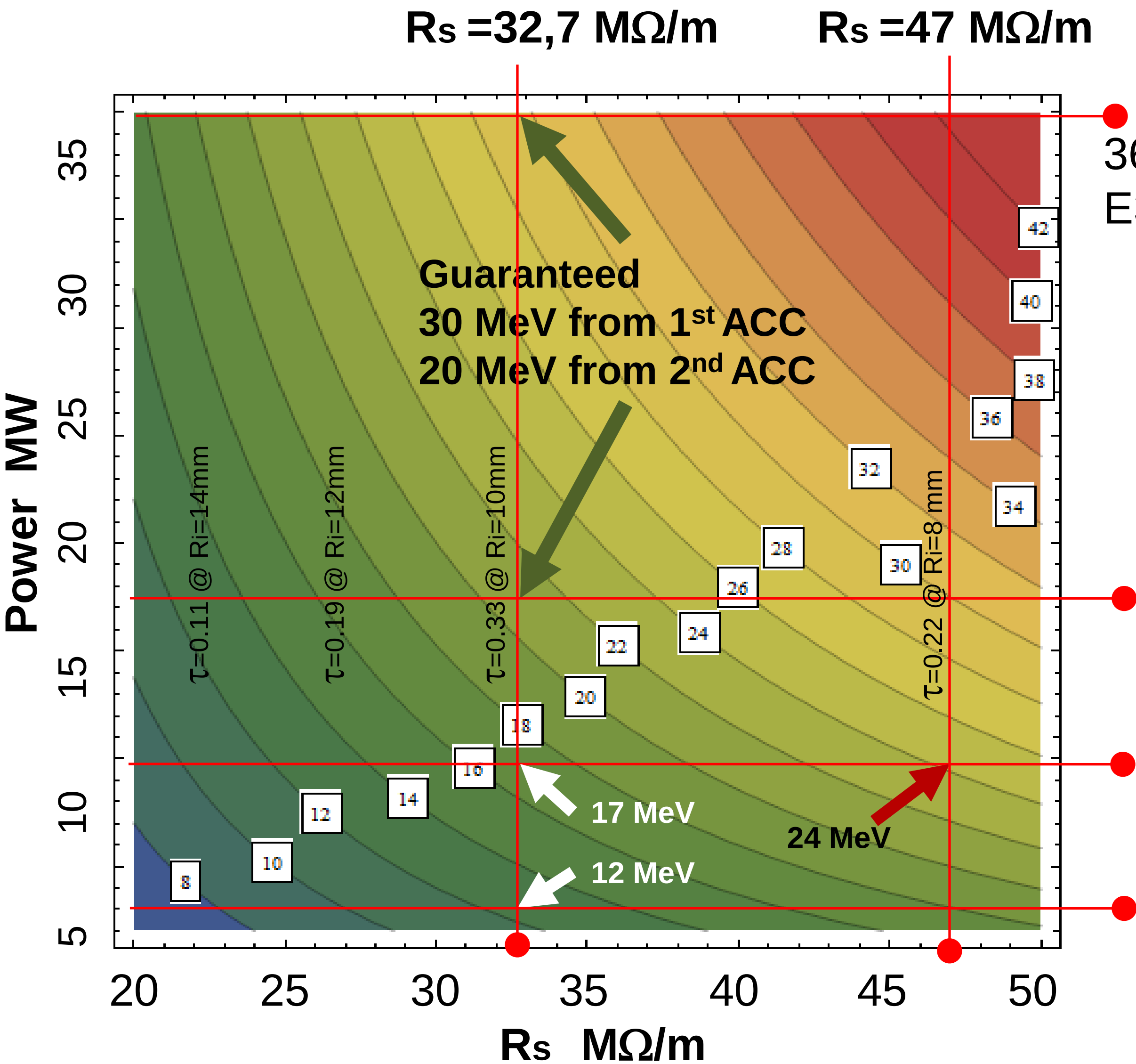
Klystron and Modulator Parameters

Type		K211	E3779	E37302	E37310	K1	K2-2	K2-3
P_{Out}(peak)	MW	7	6	45	50	26	115	160
Efficiency	%	40	42	43	43			
Gain	dB	31	49	51	52			
Pulse Length	µs	4.5	2.5	3	4.5			
Rate	pps	50	400	100	50			
V_{beam}	KV	200	145	325	340	130-190	250-360	280-450
I_{Beam}(peak)	A	92	105	400	420	110-140	200-350	230-450

Max Acceleration [MeV] in 1,6 m section



36 MW from one 37 MW E37302 Toshiba klystron

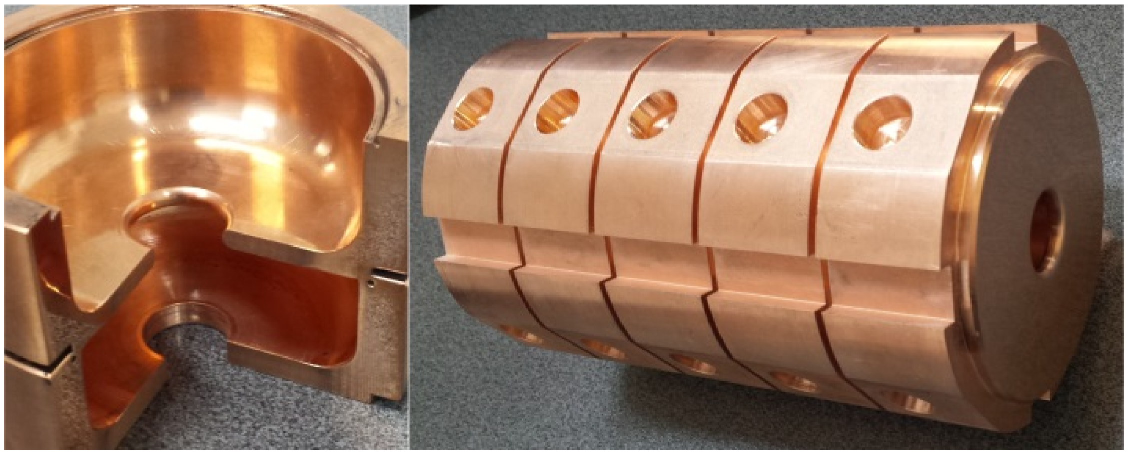
18 MW

12 MW combined from two 7MW klystrons

6 MW from one 7MW klystron

Prototyping

The 5 cell prototype was produced and tested in our workshop. Few cups are produced and measured in CANDLE Mechanical Measurement Lab



Brazing test with 2 cells (left) and 5 cell prototpe (right).

Mechanical measurements results.

	Design tolerance µm	Measured tolerance µm	Reproducibility µm
Cup diameter	-20	-10	± 2÷3
Height	-15	-6	
Iris radius	-10	-4	
Surface roughness	0.005		

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Main Waveguide parts are purchased

Main Waveguide parts -

- **motorized 45 MW phase shifter**
- **45 MW T Combiner/Splitter**
- **Two 12 MW Loads**
- **H and E bends**

are purchased

The waveguide straight sections will be produced in CANDLE workshops.

The Location of RF Equipment

- The second Modulator repaired and moved to AREAL RF hall
- MO and Libera rack moved back from Laser Room to RF Hall
- The uTCA placed in same rack with thermal stabilization

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RF Hall Layout (stage 1)

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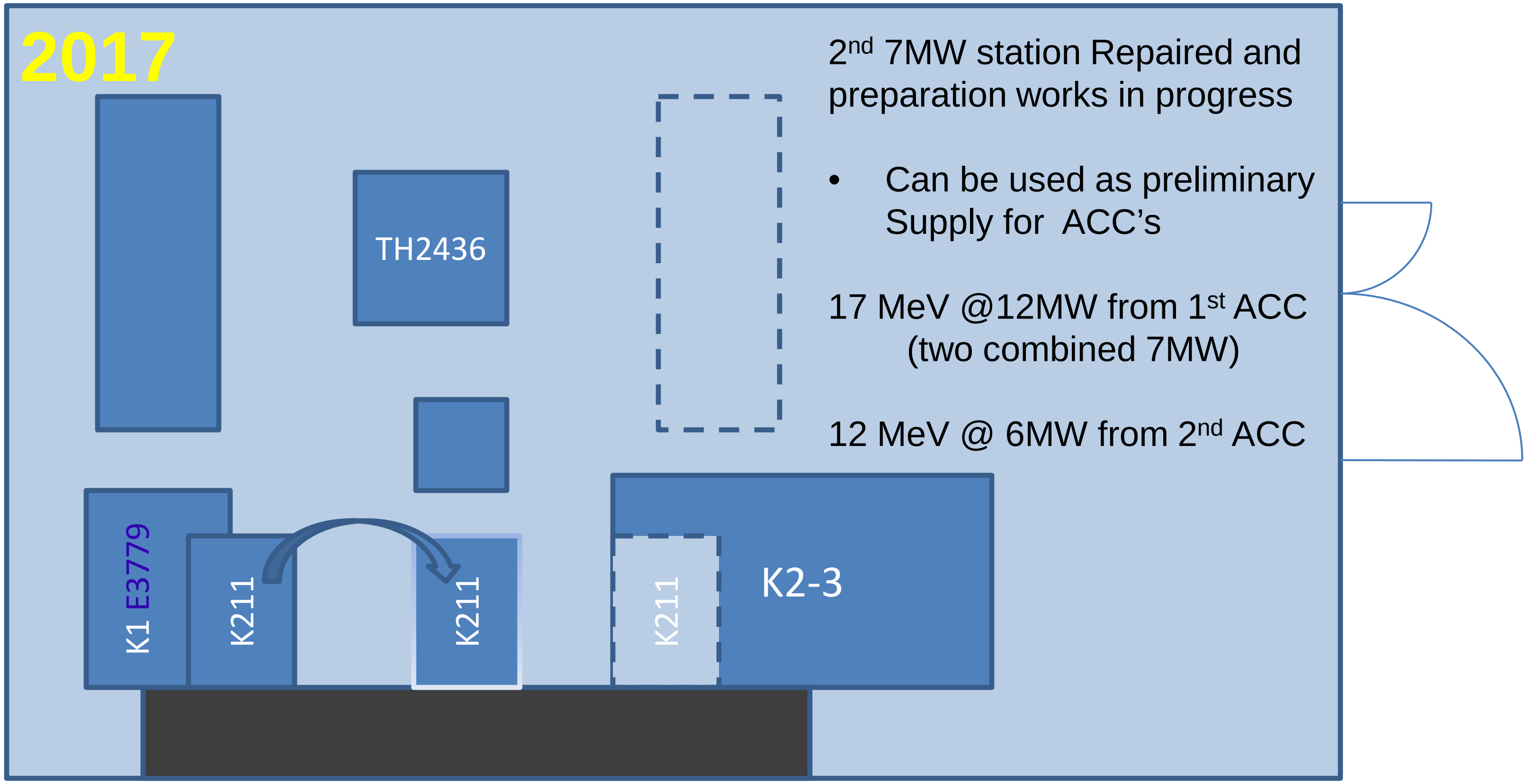
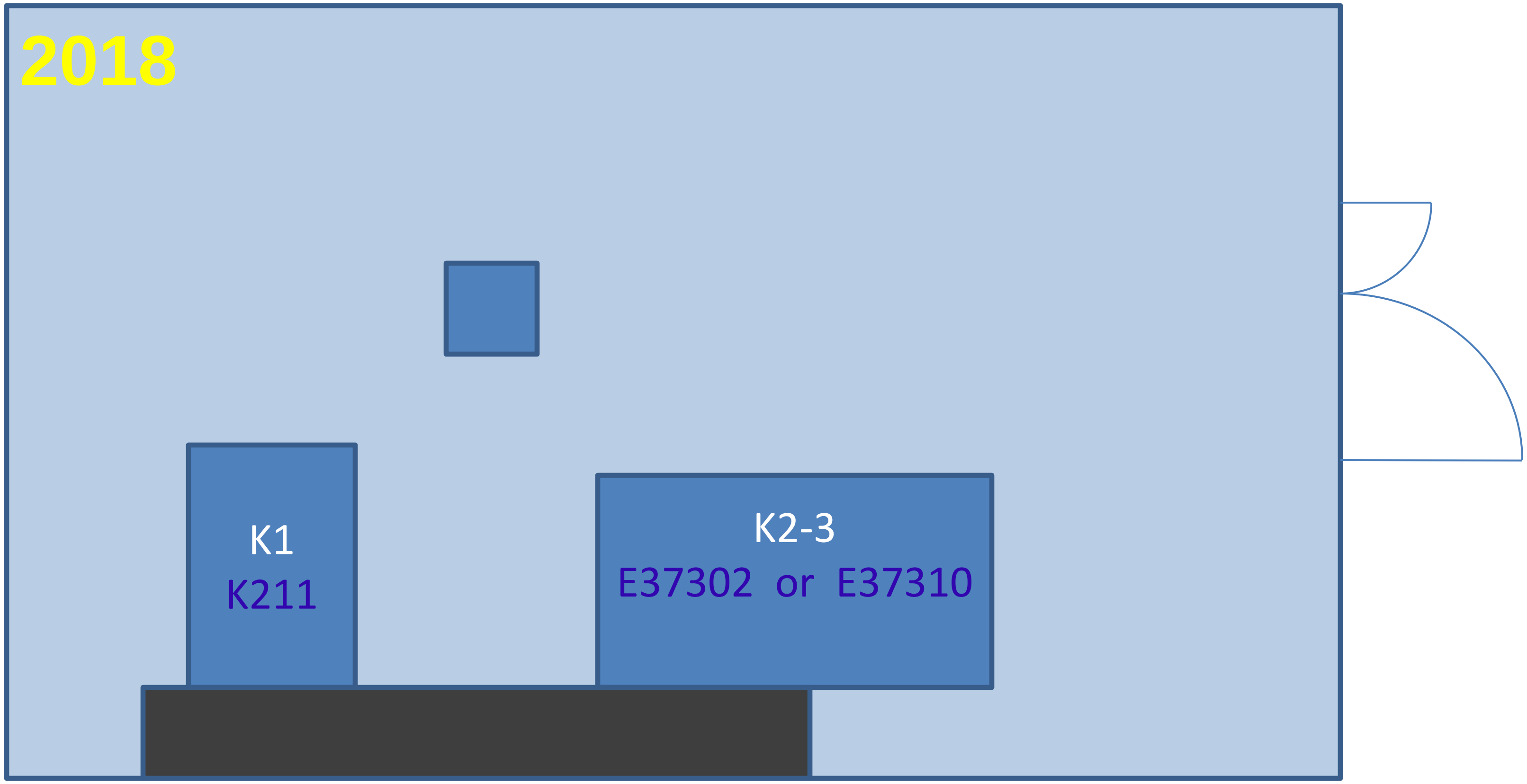


RF Hall Layout (stage 2)

Gun RF supply will be changed into modern one.

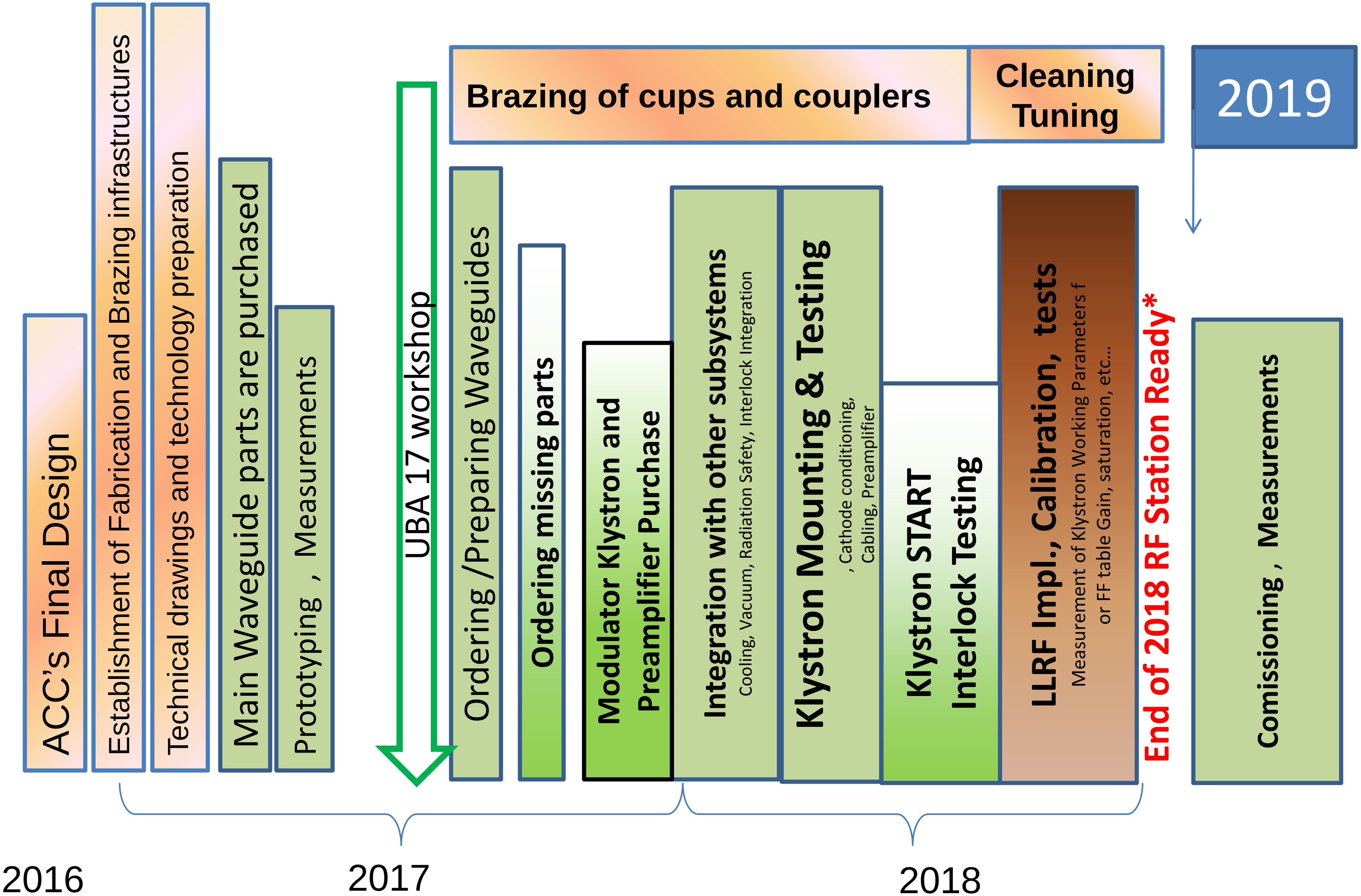
After purchasing the K3 modulator and installing on AREAL RF hall, both K211 Klystron stations with adjacent equipment will be moved to RF laboratory. It is planned to create RF test stand for further ACC prototype testing



RF Hall Layout (stage 2)

New Scandinova K-1 solid state modulator will supply k211 klystron for Gun

Time Schedule



Conclusion

- The ACC design has been done.
- The ACC's simplified prototype is constructed and tested.
- Coupler optimization has been done.
- Two couplers production are in progress.
- Main Waveguide parts are purchased.
- The negotiations with companies are in progress.
- Special devices for production, reproducibility and positioning of cups were designed and produced.
- Required regimes are developed and tested to find the optimal shape and geometry of cutting tools.
- Workshops are equipped with the modern devices for the production of ACC's cups and Couplers.
- Two soldering stations are established
    1. For soldering Cups - up to 1 m long pieces
    2. For soldering Cups assemblies and Couplers (up to 4 m)
- Construction and development of sections' production is in progress.

Critical points:

- Final cleaning and tuning: DESY
- Preamplifier (45 dB gain, 55-57 dBm output) manufacturers?

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Thank You for Attention!!!