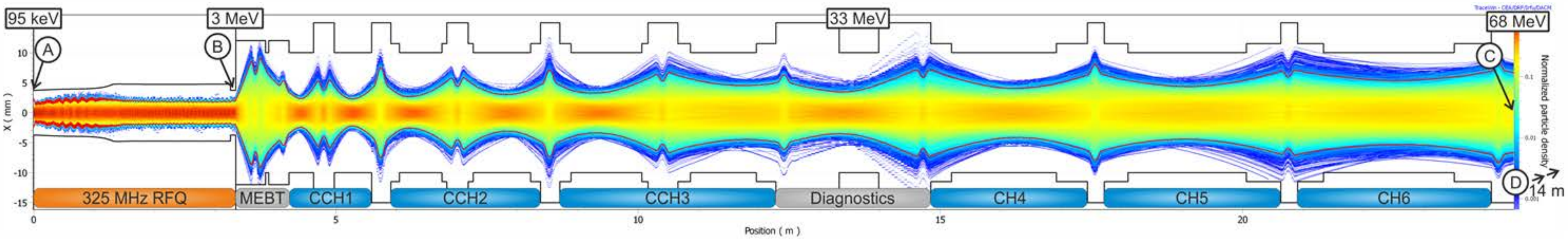
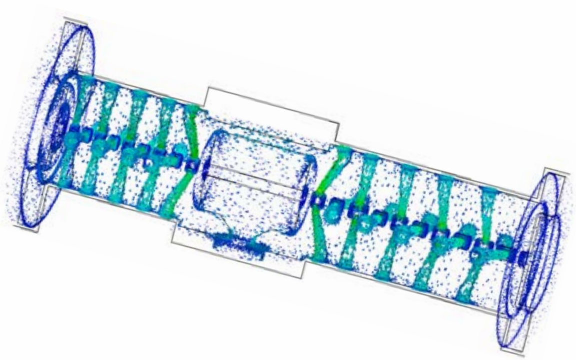


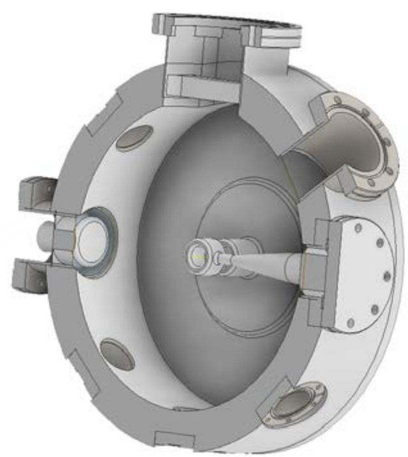
The FAIR proton linac – Beam Dynamics and Cavity Development



Dr. Hendrik Hähnel, IAP Frankfurt

GSI Accelerator Seminar
KBW Hörsaal / Zoom

Thursday, September 24, 2020



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FAIR/pLinac Overview

Scope – FAIR

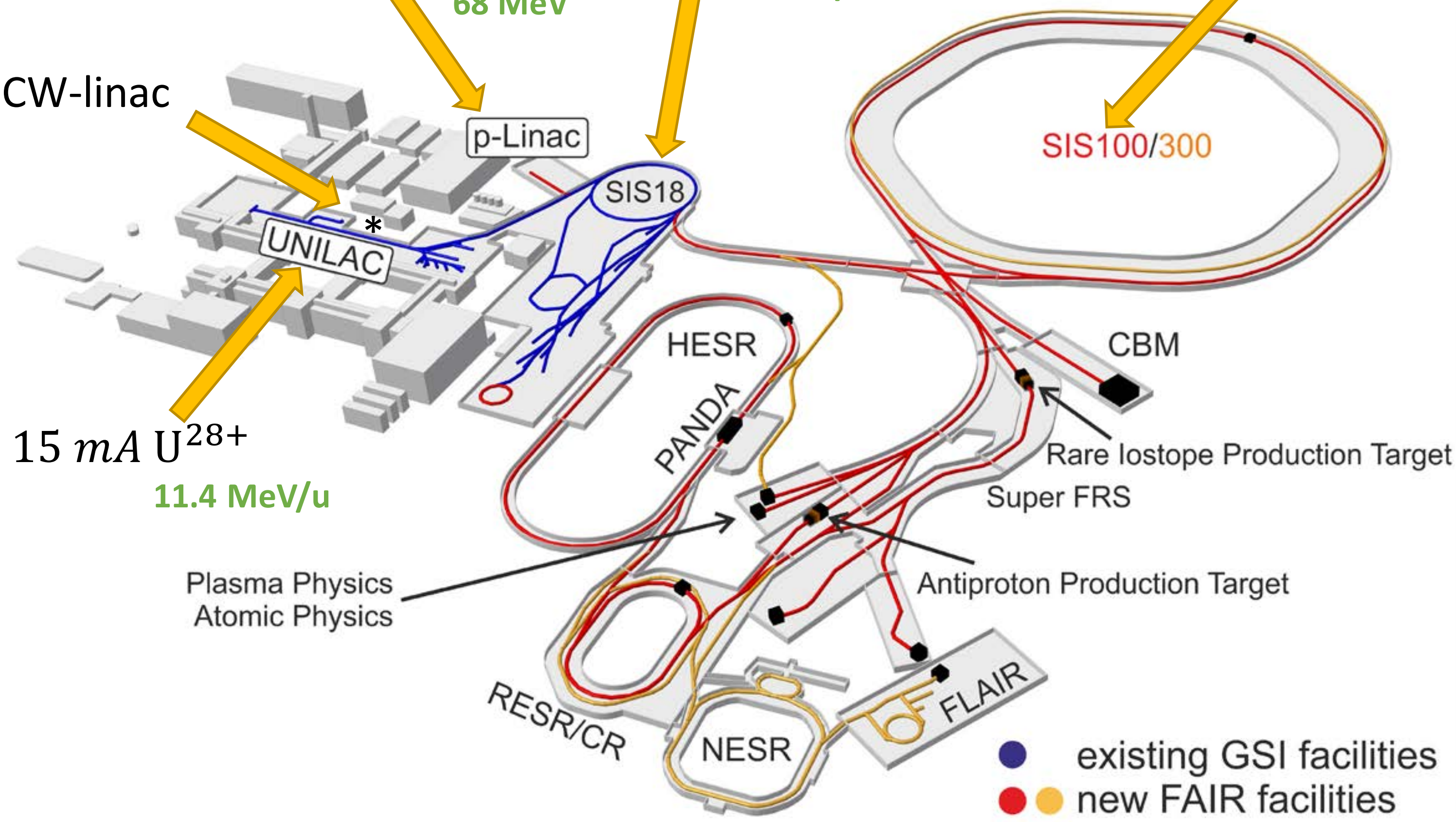
$1.25 \cdot 10^{11}$ U^{28+}/spill
$5 \cdot 10^{12}$ protons/spill
U: 200 MeV/u
p: 4 GeV

$4.5 \cdot 10^{11}$ U^{28+}/spill
$2 \cdot 10^{13}$ protons/spill
U: 2.7 GeV/u
p: 29 GeV

70 mA protons
68 MeV

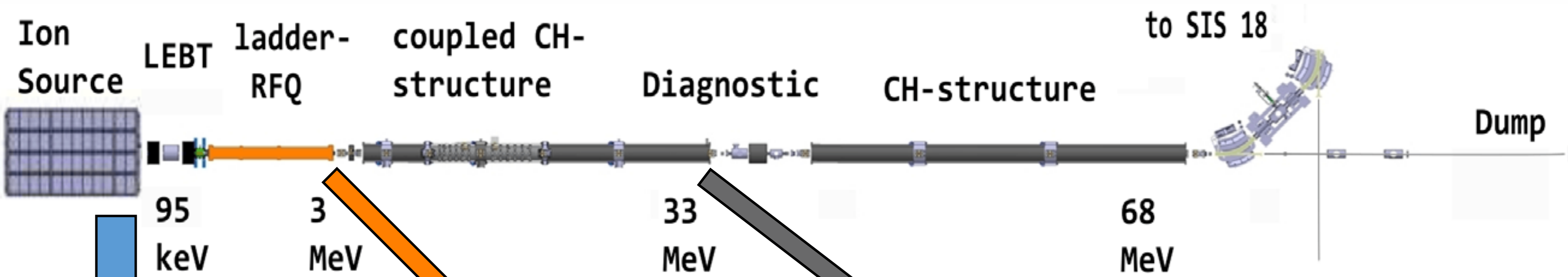
CW-linac

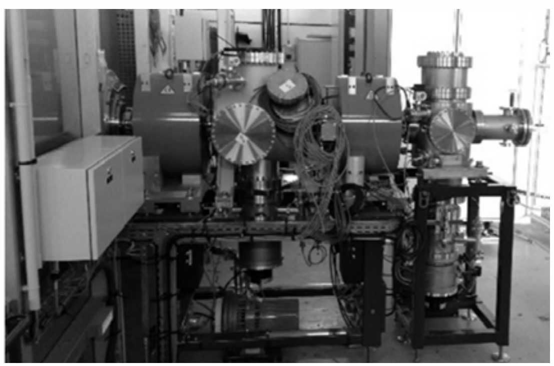
$15\ mA$ U^{28+}
11.4 MeV/u



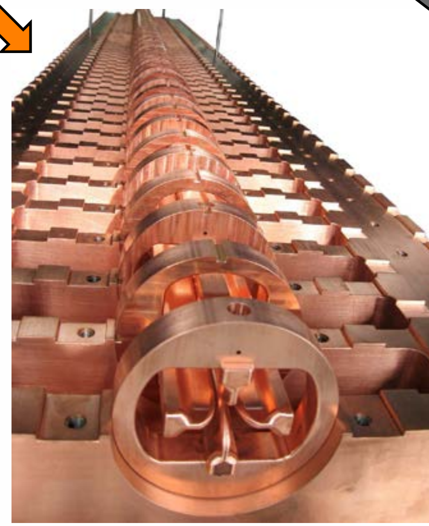
SIS18/100 numbers: [O. Kester et al., Proc. IPAC15, TUBB2]

Linac layout

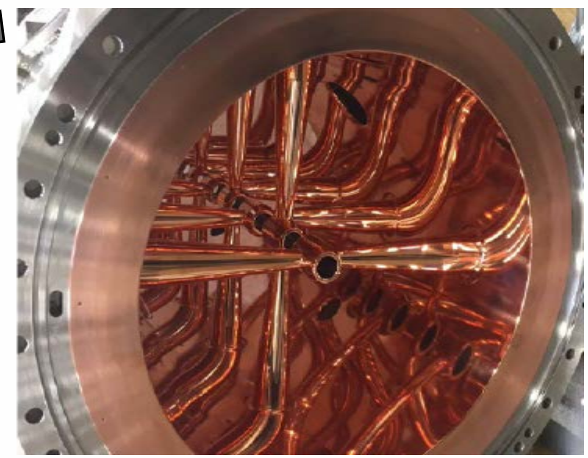




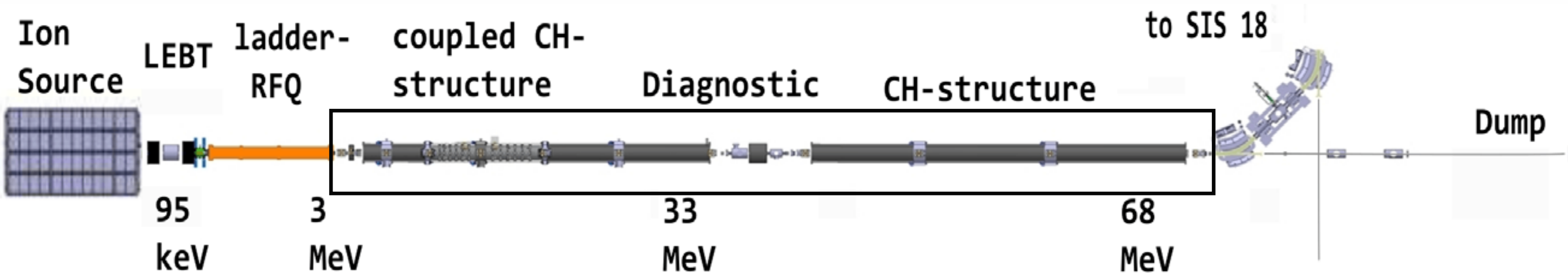
O. Tuske et al., ECRIS2016, WEPP02



M. Schütt



Linac layout



- 6 CH-DTL cavities
  - 3 coupled CH cavities (CCH1-3)
  - 3 regular CH cavities (CH4-6)
- 12 quadrupole triplet lenses
- 2 buncher cavities & 1 debuncher
- KONUS beam dynamics

Frequency: $325.224\ MHz$

Design current: $70\ mA$

$V_{eff} = 65\ MV$

$W_{out} = 68\ MeV$

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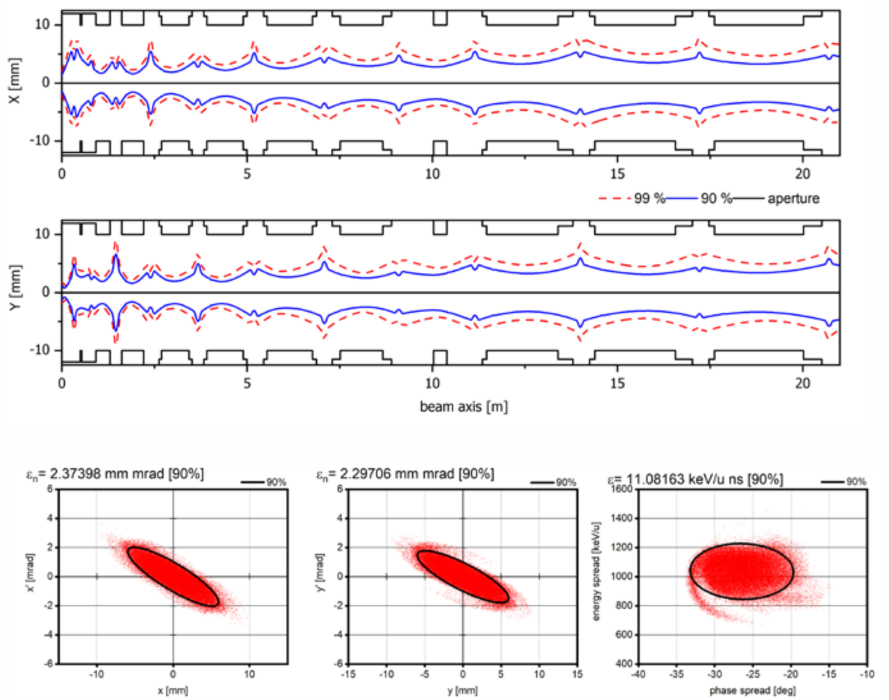
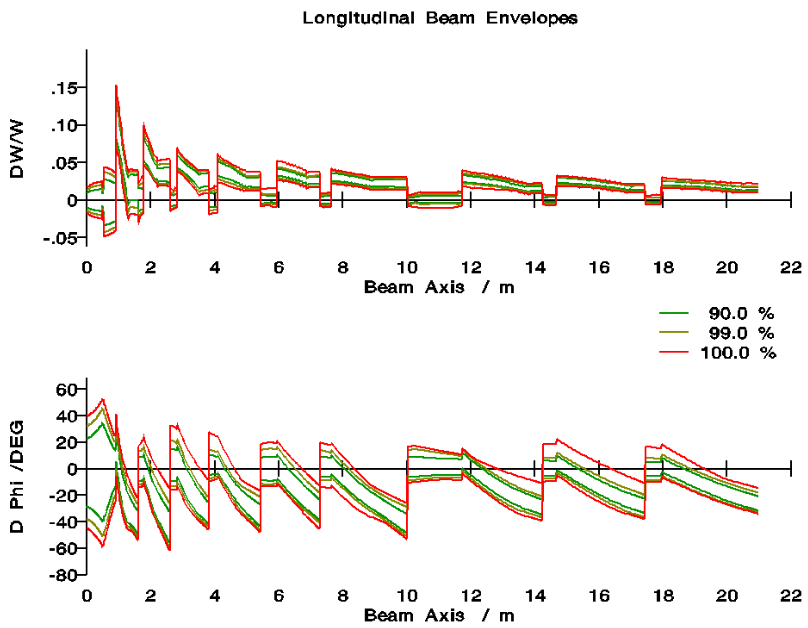
pLinac Beam Dynamics

Beam Dynamics Design

U. Ratzinger, A. Almomani, (G. Clemente)

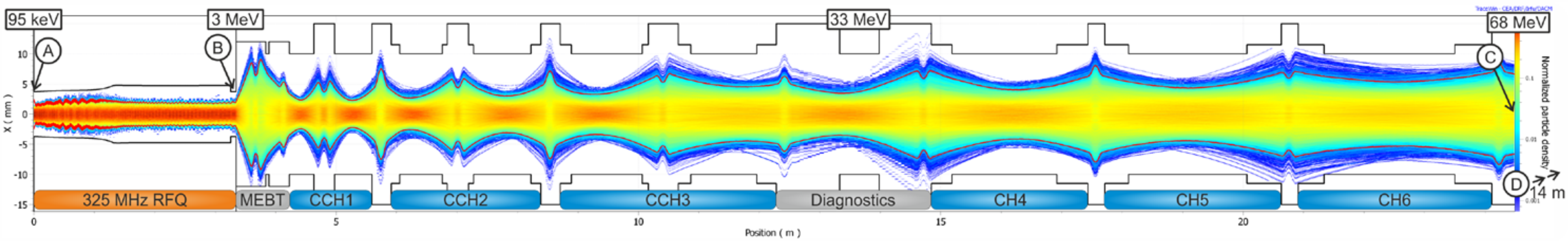
- Beam dynamics design was finalized @ IAP in 2017
- Based on KONUS beam dynamics





Since then, Beam line changes due to mech. integration issues were tracked and always confirmed with beam dynamics.

pLinac End-to-End



- Simulation of RFQ* using Toutatis
  - Imported vane geometry for best agreement between RFQGen & Toutatis
- 3D CST Field maps for all six CH-type cavities (final state)
  - Except for bunchers (modeled as thin gaps)
  - Conversion by MATLAB script
- Additional 14 m drift + debuncher cavity (6-gap, 110 kV)
- Simulation for $\sim 75\ mA$ protons
  - 100,000 macro particles
  - Manual tuning of all cavity phases and amplitudes

*RFQGen beam dynamics & design by M. Syha

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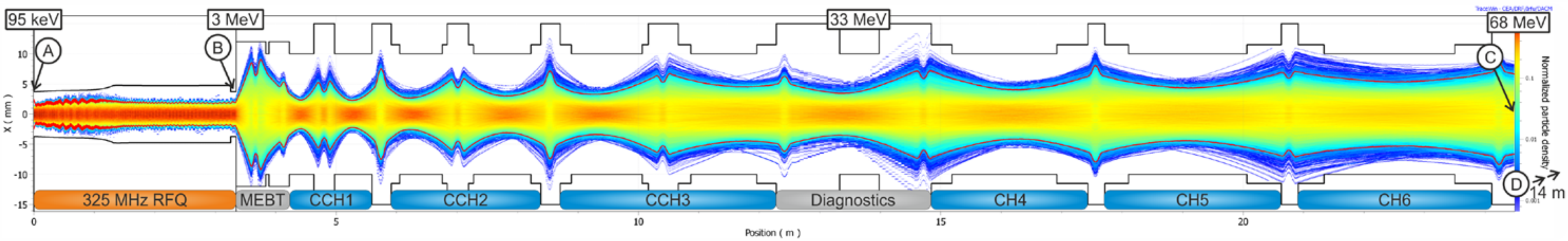
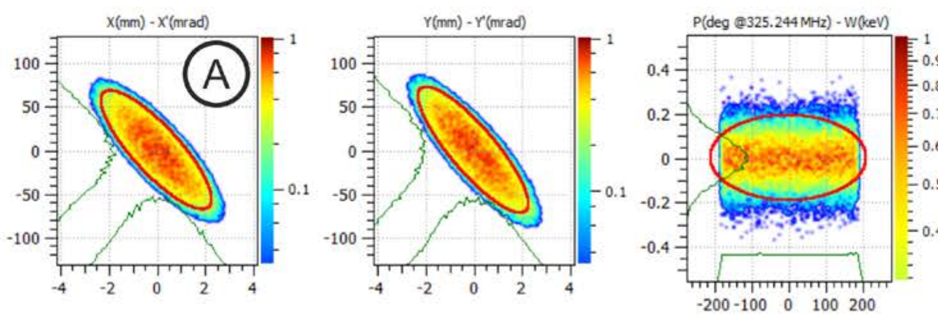
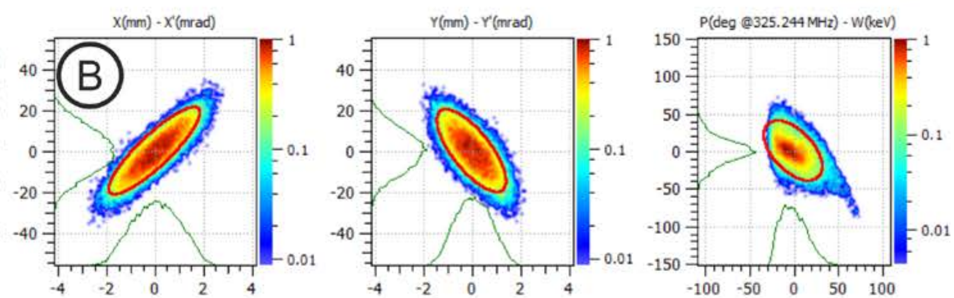
pLinac End-to-End – Beam Evolution



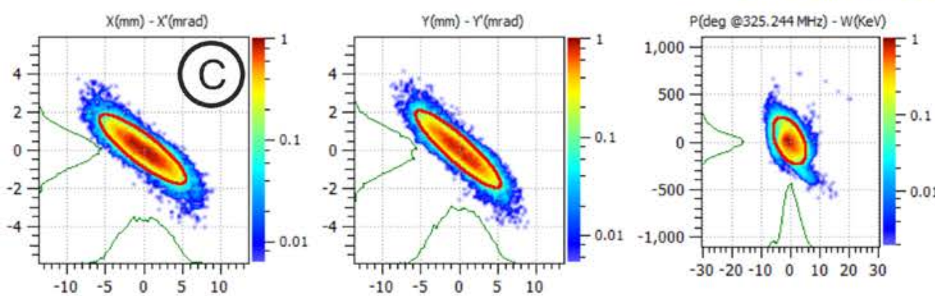
RFQ entrance (95 keV):



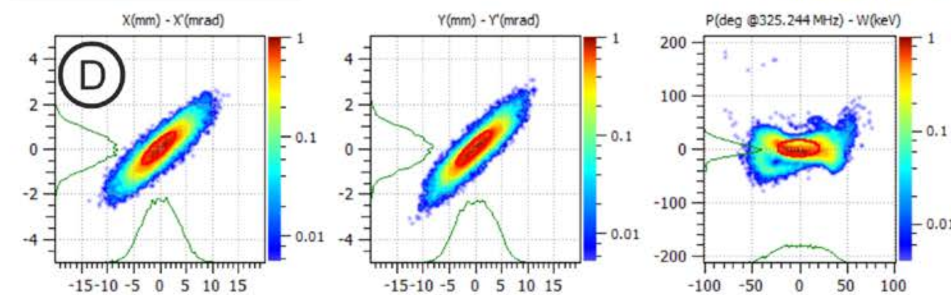
RFQ exit (3 MeV):



pLinac exit (68 MeV):

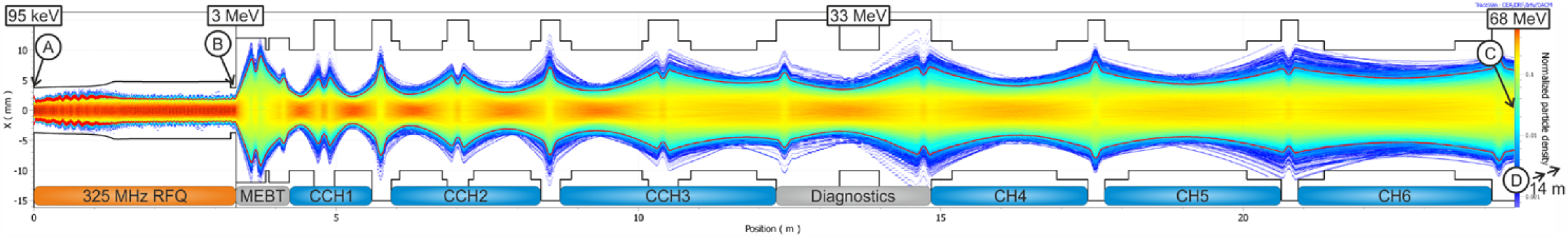


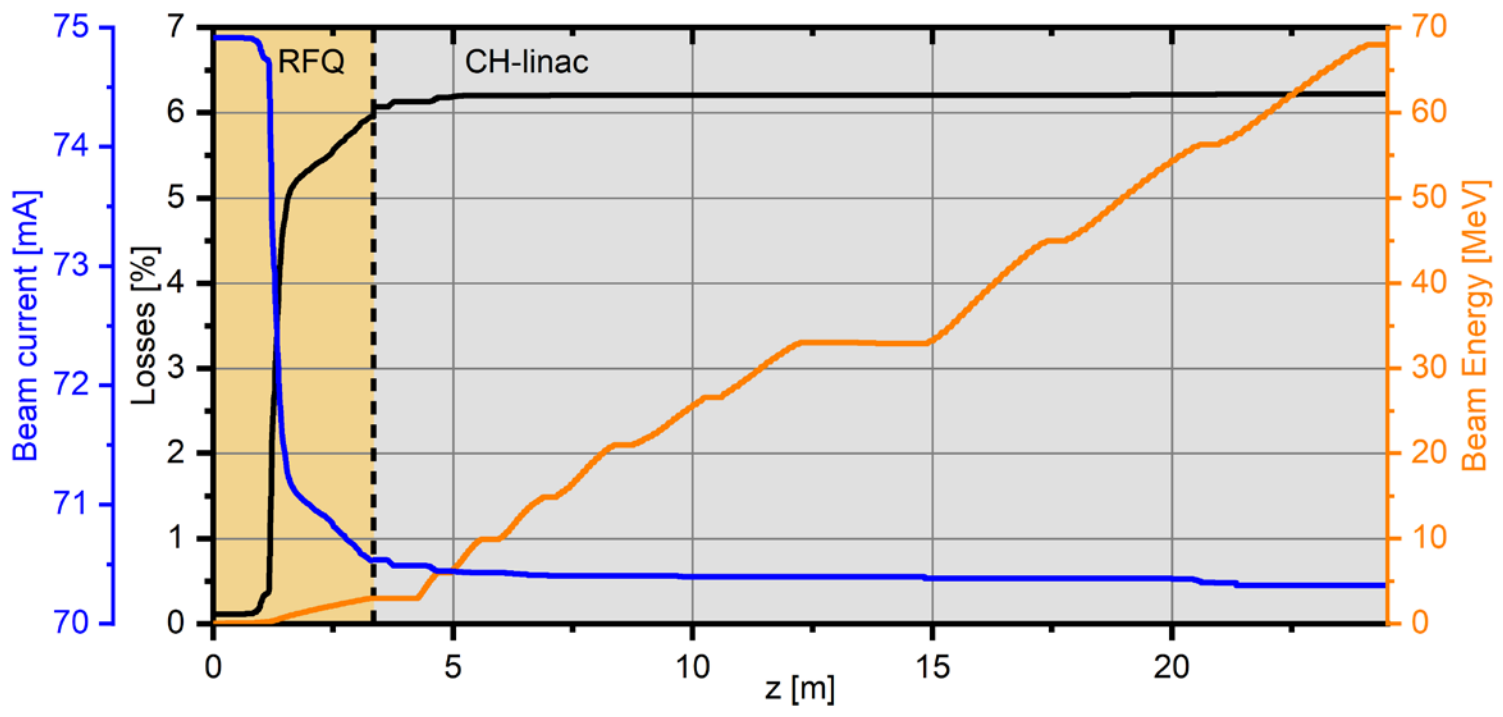
Debuncher exit:



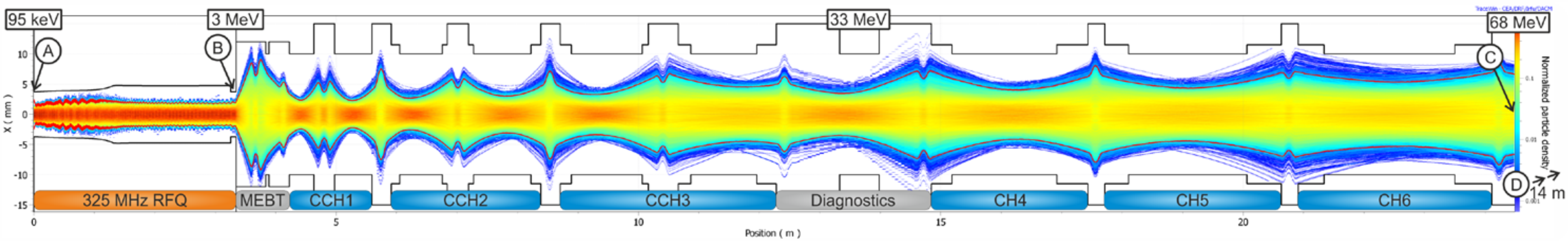
$$\Delta W/W = \pm 2.2 \cdot 10^{-4} \; (\Delta p/p = \pm 1.14 \cdot 10^{-4})$$

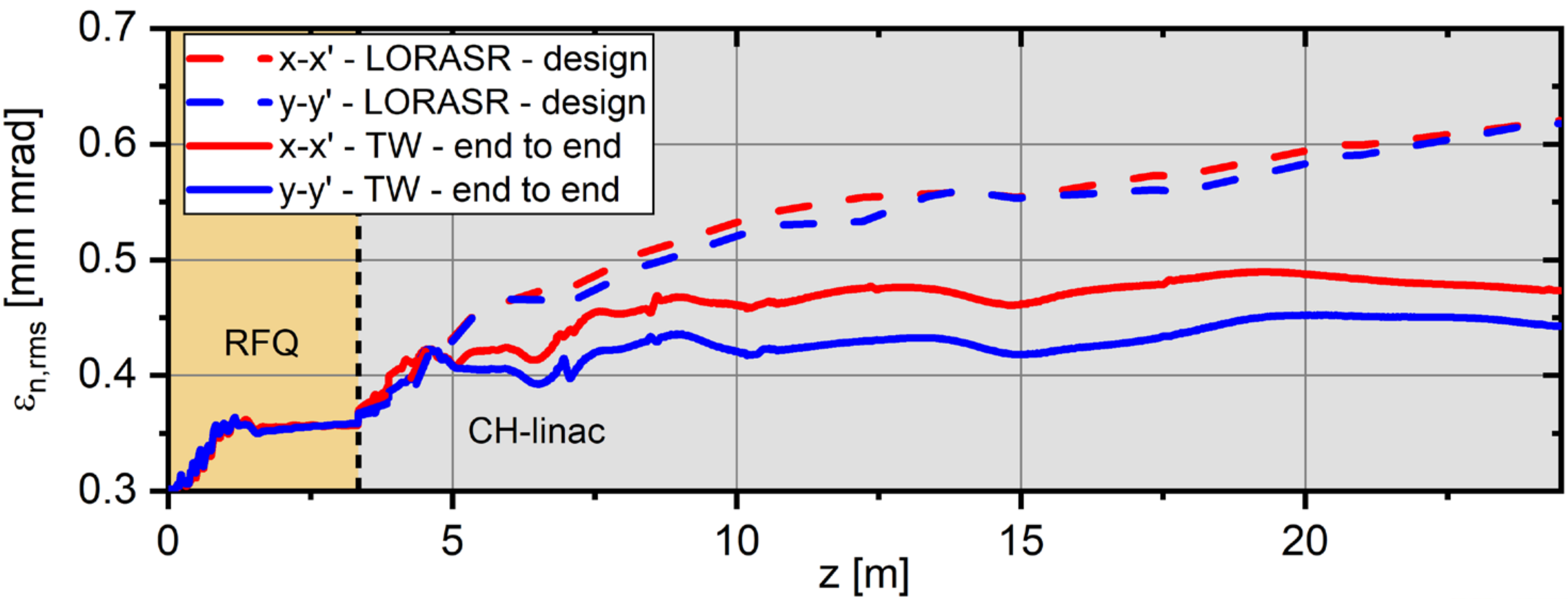
pLinac End-to-End – Beam Parameters





pLinac End-to-End – Emittance





*LORASR with 6D waterbag

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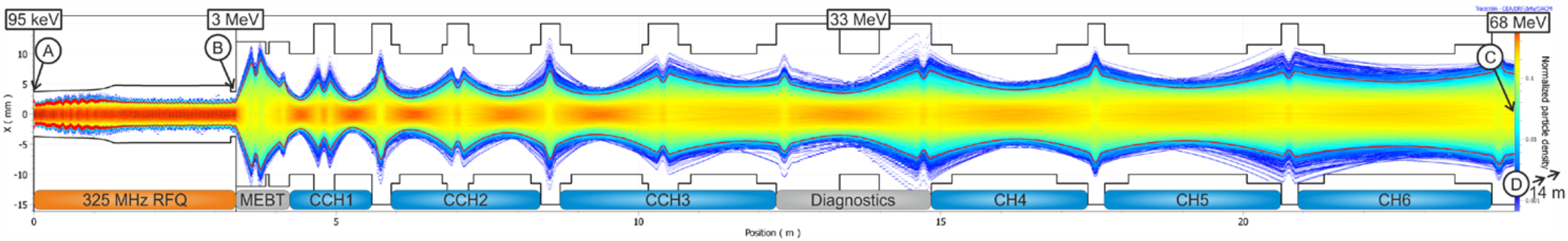
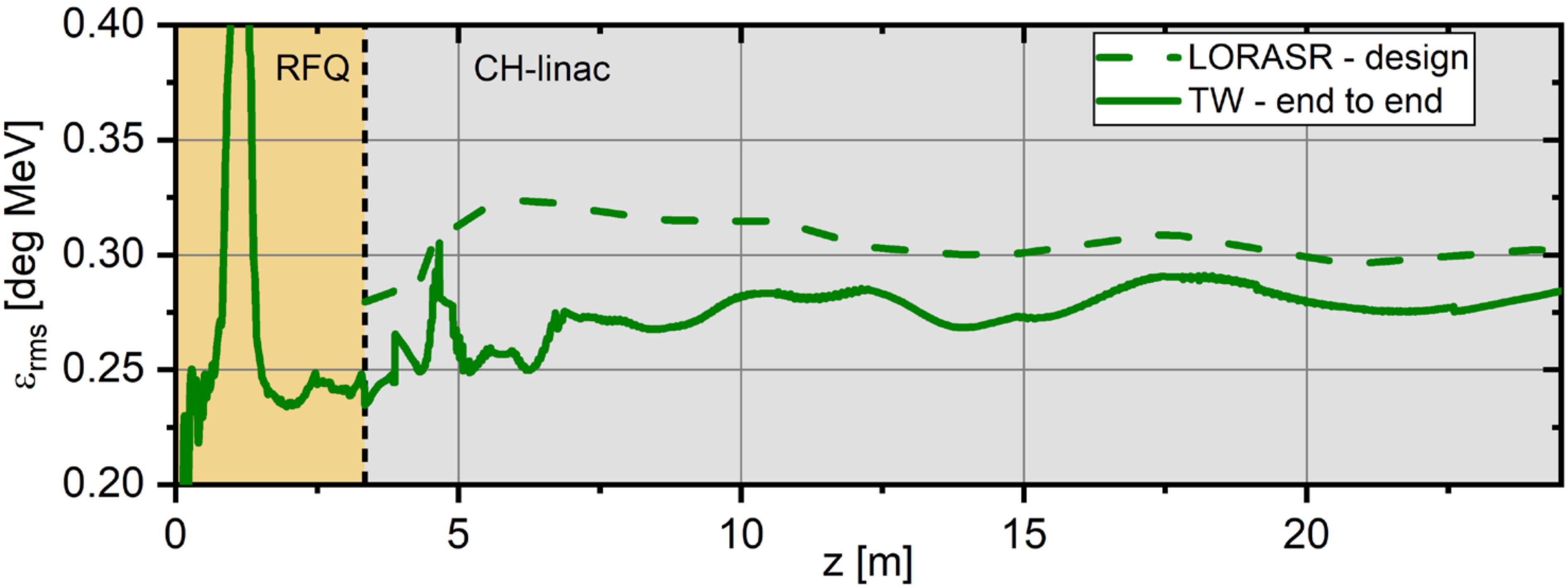
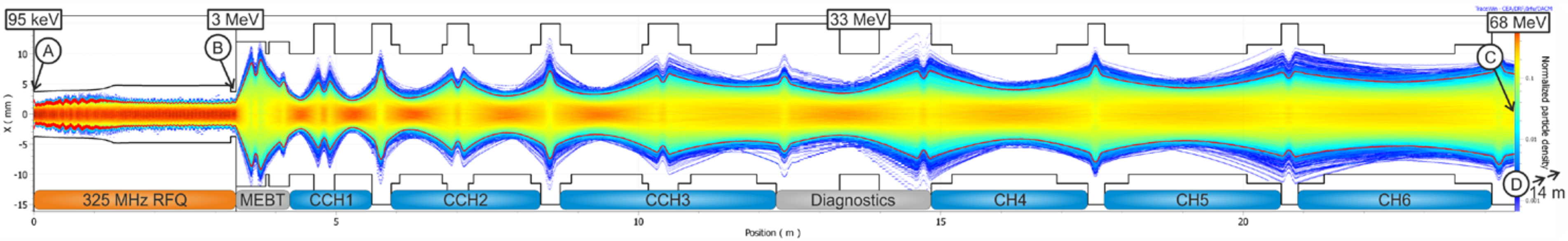
pLinac End-to-End – Emittance





*LORASR with 6D waterbag

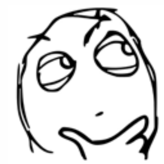
pLinac End-to-End – Conclusions



- Transverse matching seems a bit off in the last bit… was fixed later
- Combination of RFQ and CH-linac worked nicely
- Results very much confirmed the performance of the pLinac design

<u>What is really interesting?</u>

- Emittance growth is lower? than in LORASR simulations



- KONUS cavities can be fine tuned for emittance while keeping almost identical output energy
- "Thin-gap" simulations were somehow "off" in the longitudinal plane

Thin-Gap / Fieldmap / LORASR

Simulations of complex beam dynamics e.g. KONUS, EQUUS, APF

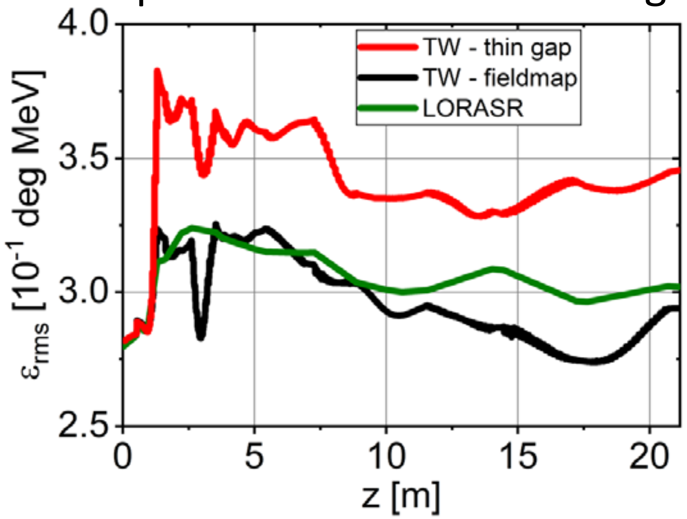
- Thin Gap simulations („one step per gap“) can produce unrealistic results

Comparison of many projects* shows the following ranking

<u>Best to worst</u>

1. TraceWin with 3D fieldmaps
2. LORASR & TraceWin with LORASR Ez(z) fieldmaps
3. TraceWin with ThinGap approximation

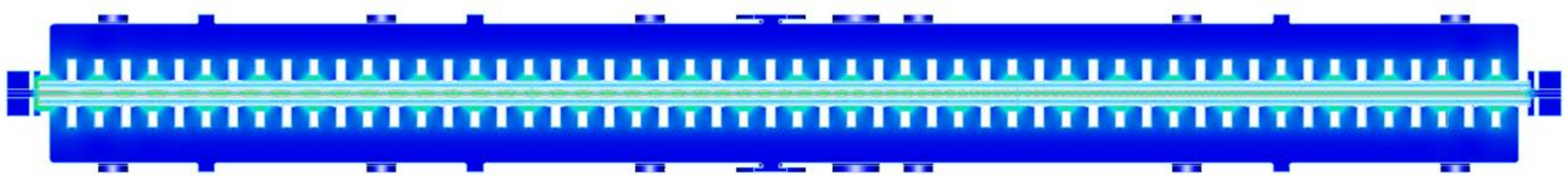
<u>Example:</u>
pLinac with same waterbag

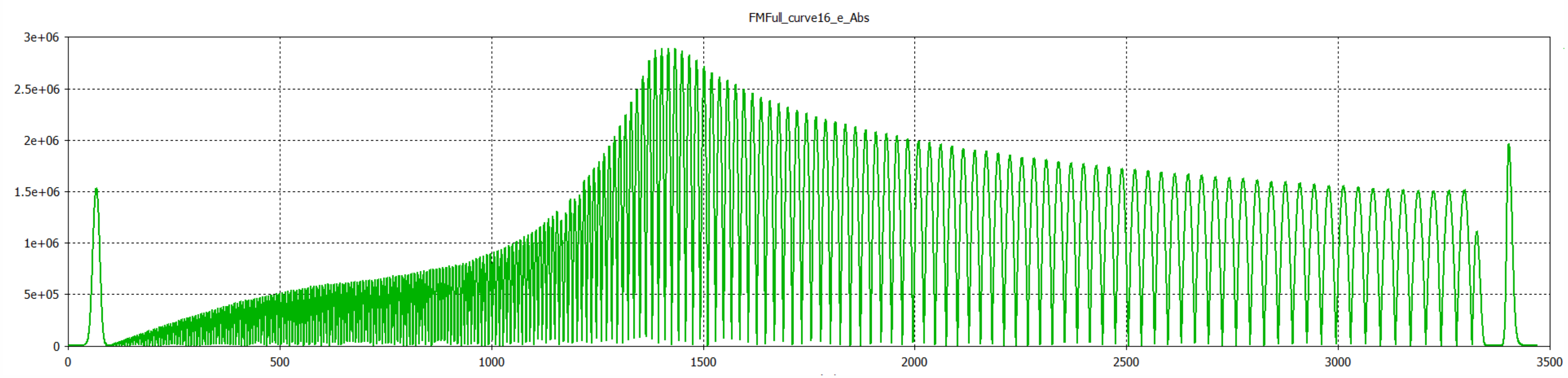


* ”many” are:
Poststripper IH-DTL (3D FM,$E_z(z)$, TG, LORASR)
pLinac CH-DTL (3D FM,$E_z(z)$, TG, LORASR)
HILac IH-DTL ($E_z(z)$, TG, LORASR)
LILac IH-DTL ($E_z(z)$, TG, LORASR)

RFQ Simulations

RFQ Fieldmap Simulations

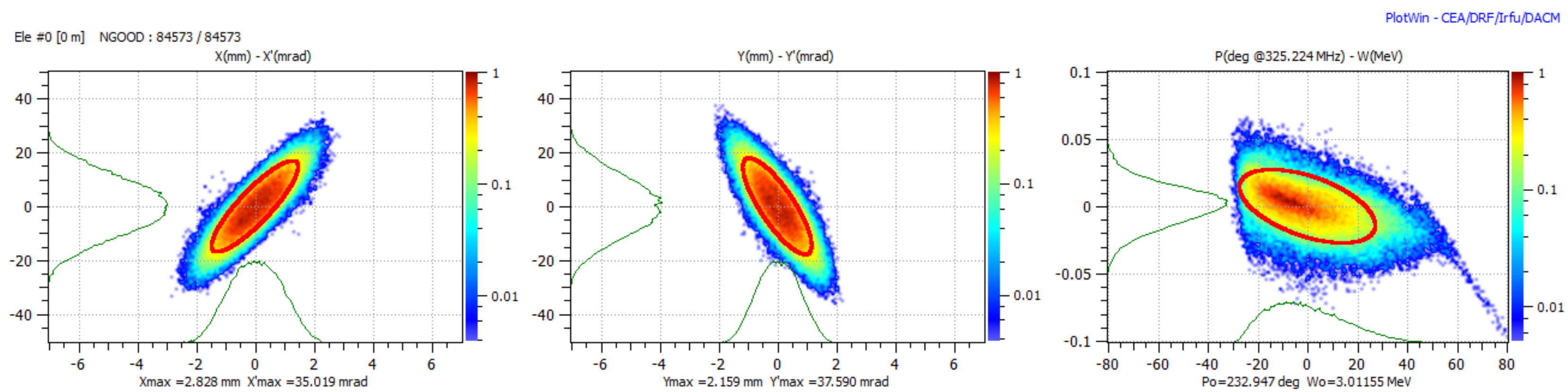




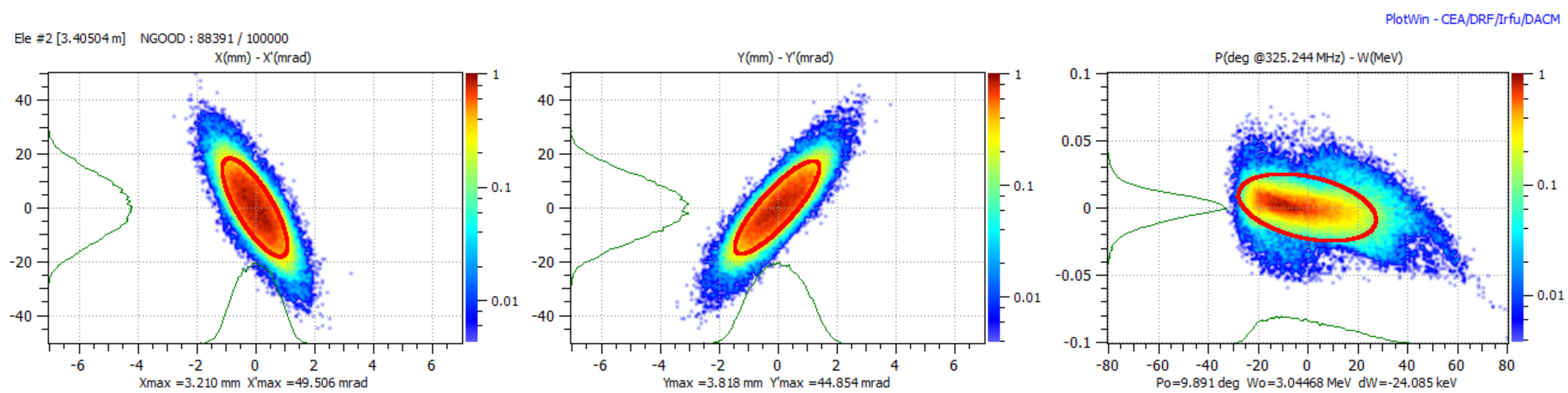
- CST Simulation with modulated vanes (M. Schuett)
- Fieldmap export for the whole RFQ ($x, y = \pm 5\ mm$)
- Simulation in TraceWin
  - Including long. fringe fields

RFQ Fieldmap Simulations

RFQGen (M. Syha)

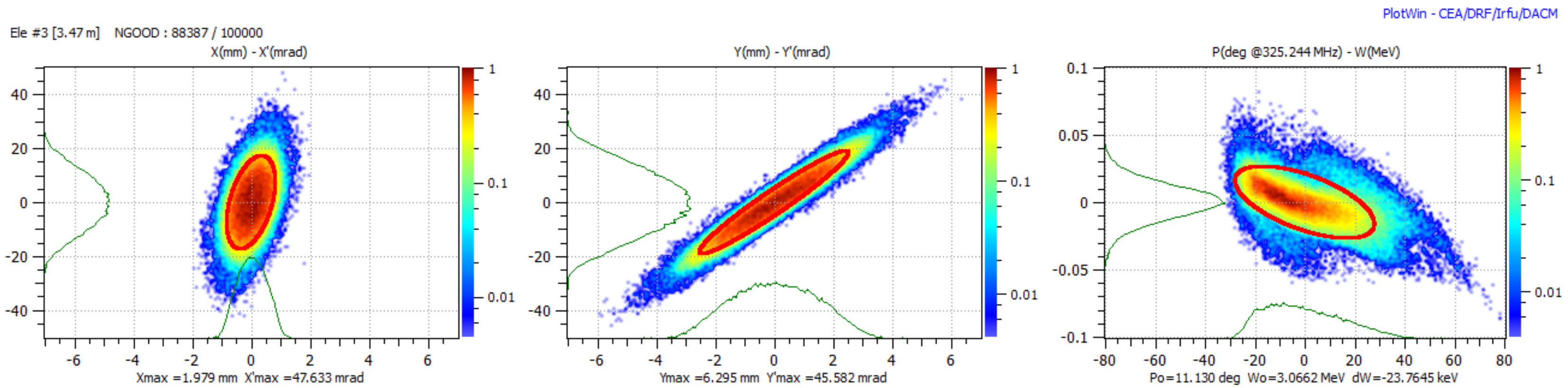


TraceWin RFQ Fieldmap (at the same position)

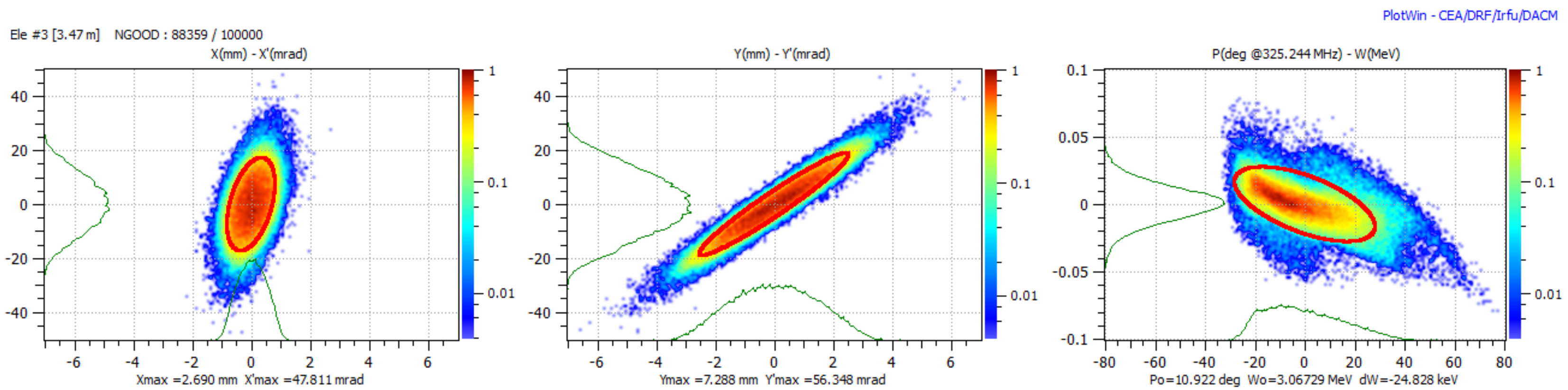


RFQ Fieldmap Simulations (Stepsize)

0.5 mm steps



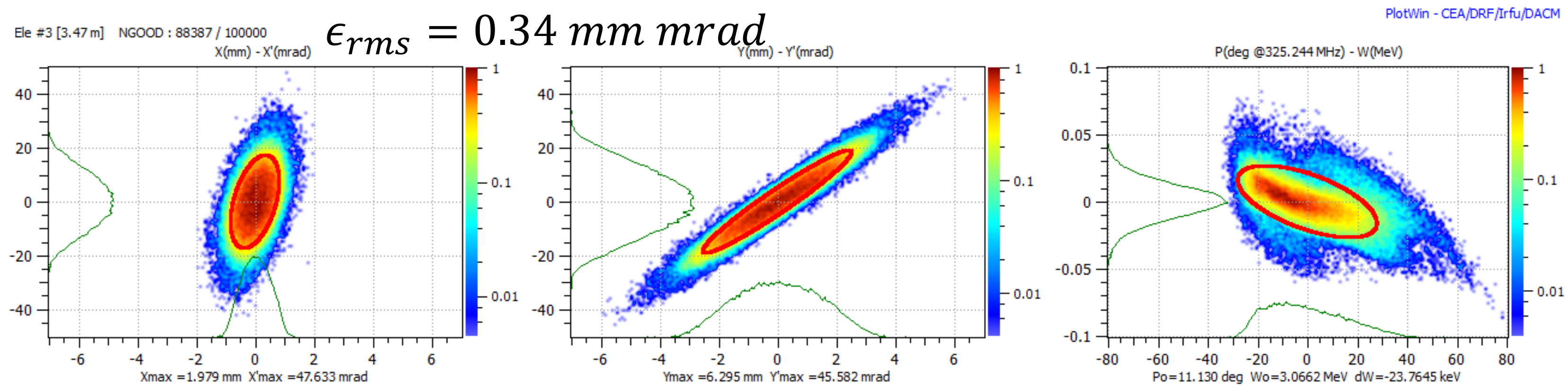
0.1 mm steps



RFQ Fieldmap Simulations (Stepsize)

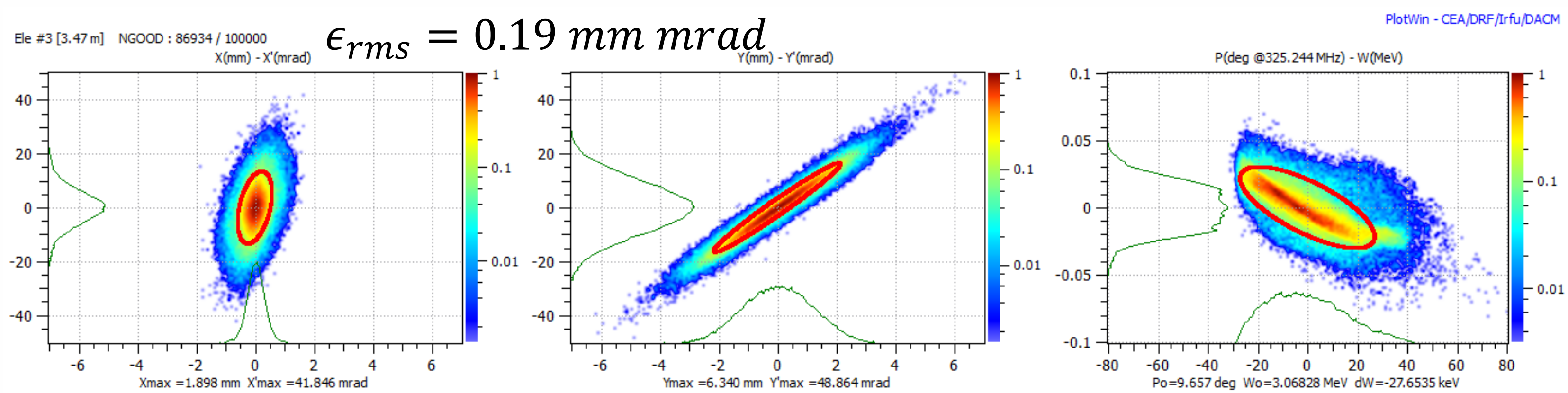
0.5 mm steps (1.000 calc steps per meter)

$\epsilon_{rms} = 0.34\ mm\ mrad$



0.5 mm steps (200 calc steps per meter)

$\epsilon_{rms} = 0.19\ mm\ mrad$



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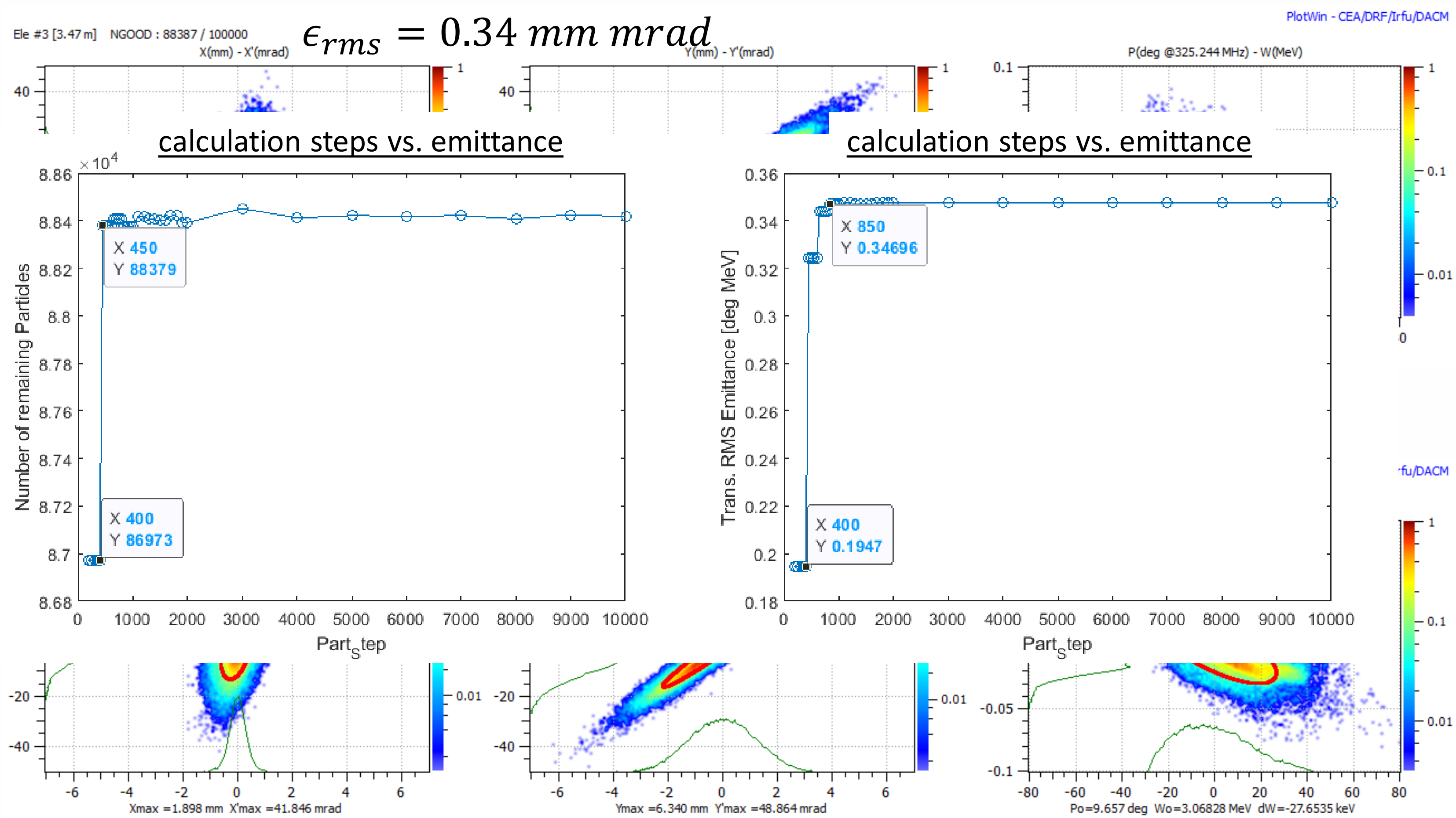
RFQ Fieldmap Simulations (Stepsize)

0.5 mm steps (1.000 calc steps per meter)

$$\epsilon_{rms} = 0.34\ mm\ mrad$$



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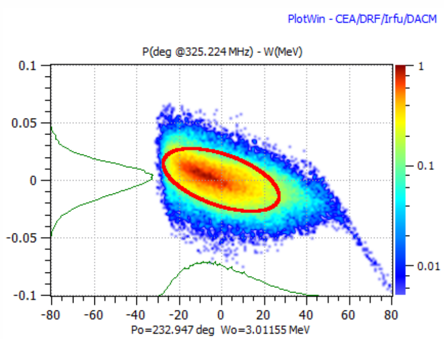
BUT: Not everything is peachy

Fieldmap calculations neglect:

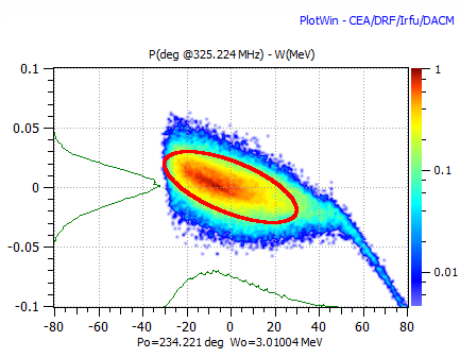
- Image charges on the vanes
- Neighboring bunches (space charge)

RFQGen simulations show, that these effects have an impact (M. Syha)

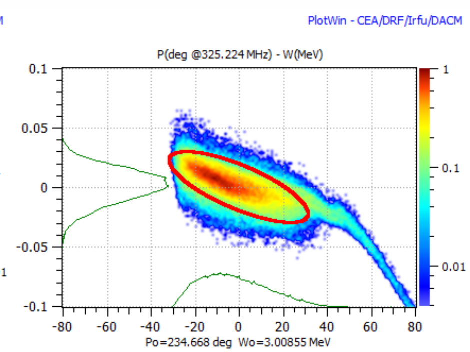
Both on



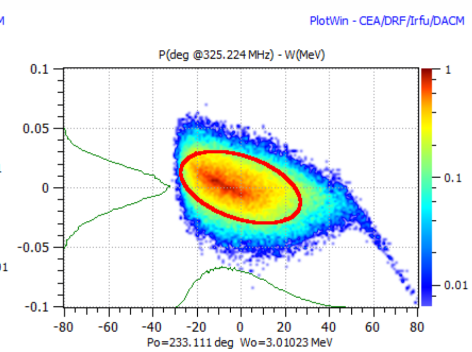
Both off



Only neighbors



Only image-ch.

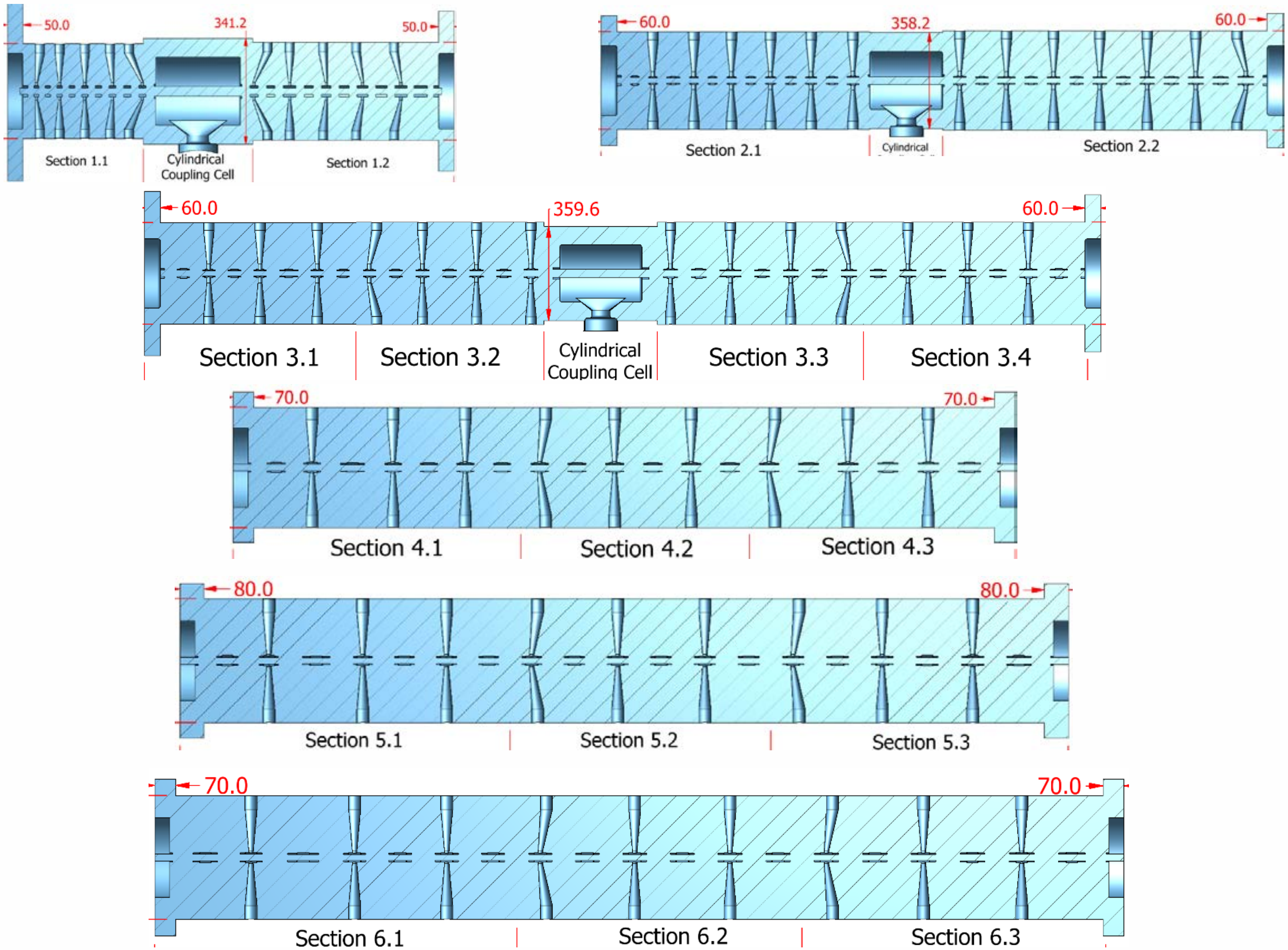


- They also differ in transmission and emittances

CH-Cavities

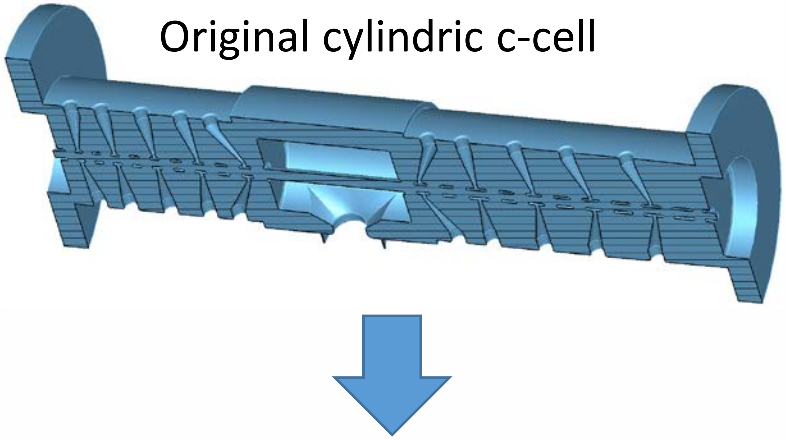
Cavities – End of 2017

A. Almomani, M. Busch, F. Dziuba

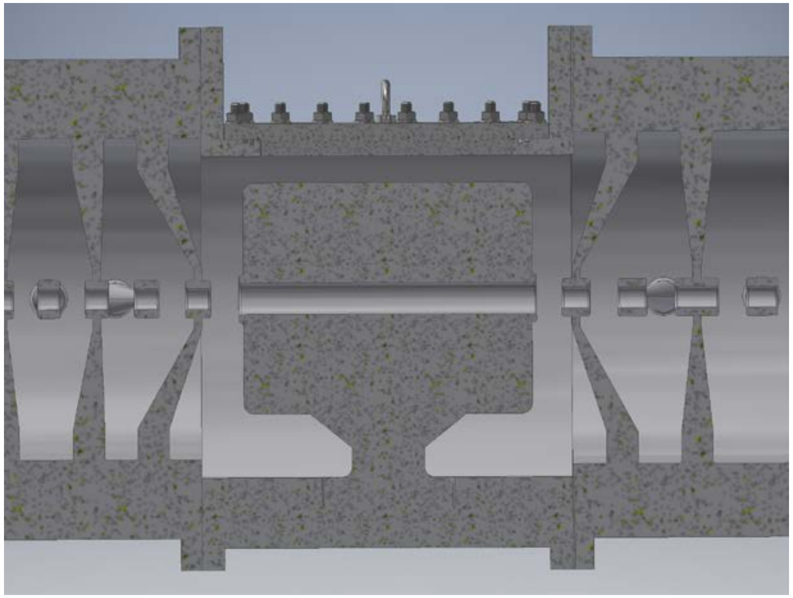


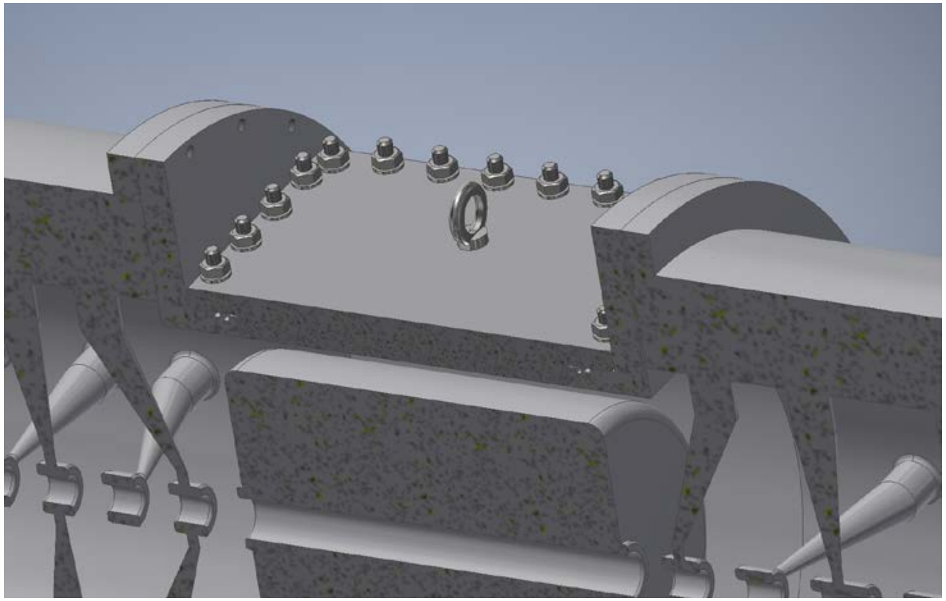
New Coupling Cell

Original cylindric c-cell

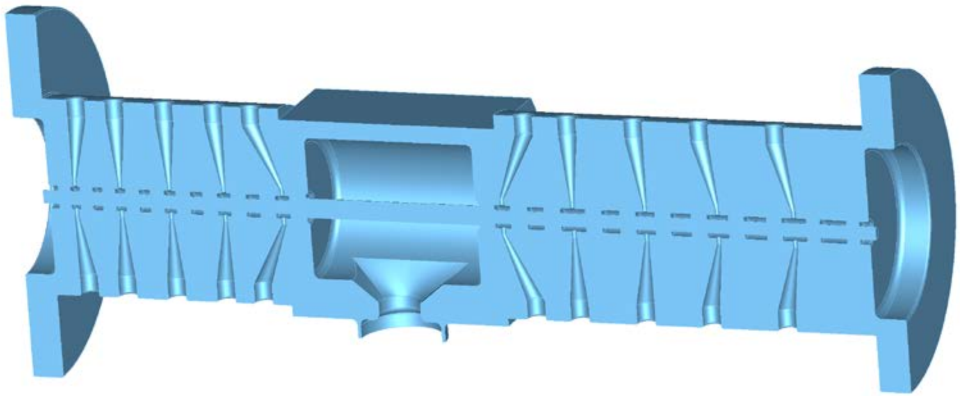


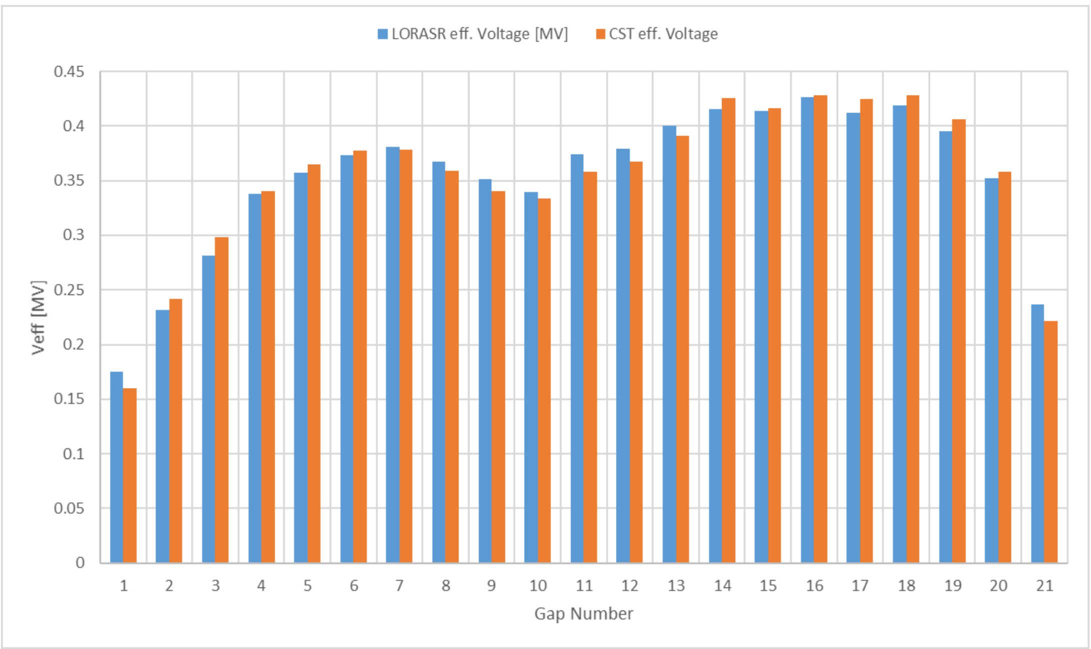
New c-cell with lid





CCH1 Final State





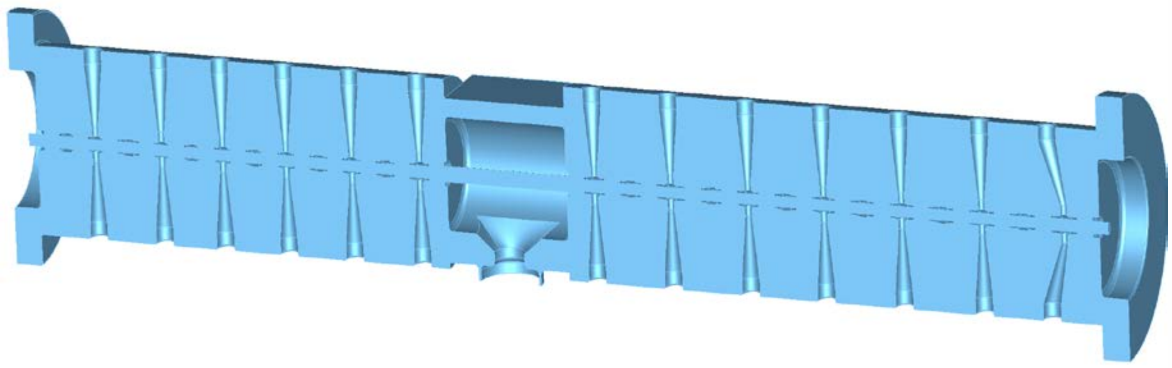
CCH1 is considered final in terms of the rf-design.

Tuning of the voltage distribution with new c-cell is completed.

New c-cell has no impact on Z_{eff}.

	Original	**Final „Hi res“**
$f\ [MHz]$	325	**324.2**
$Z_{eff}\ \left[\frac{M\Omega}{m}\right]$	53.5	**52.3**
ΔV_{sec1}	-	**-0.5 kV**
ΔV_{sec2}	-	**+0.5 kV**
$\Delta f_2\ [MHz]$	1.83	**1.6**

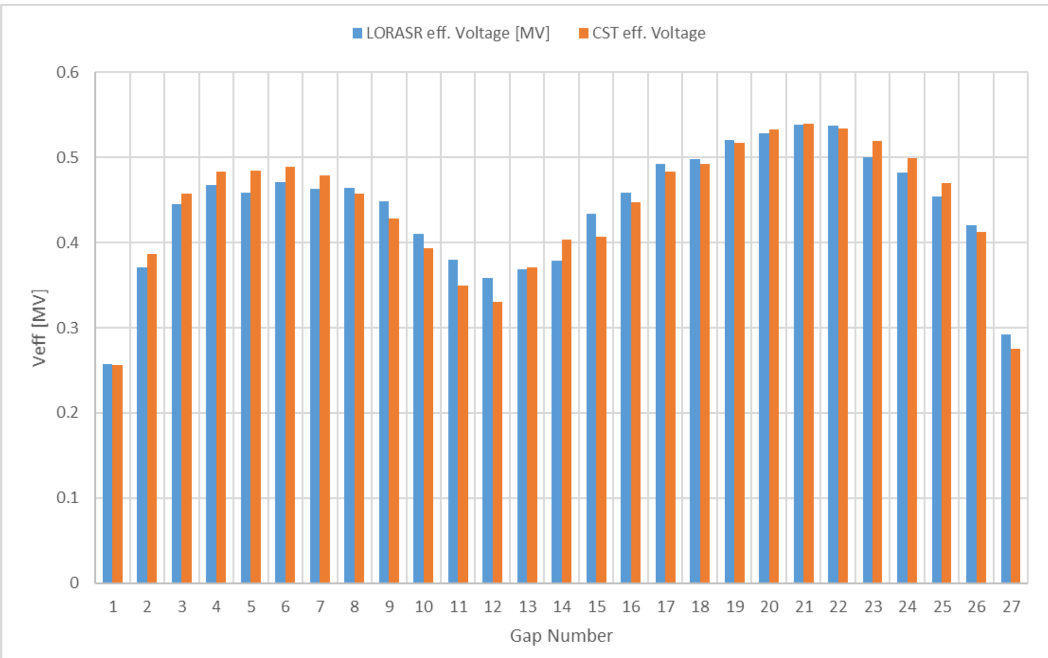
CCH2 Final State



CCH2 is considered final in terms of the rf-design.

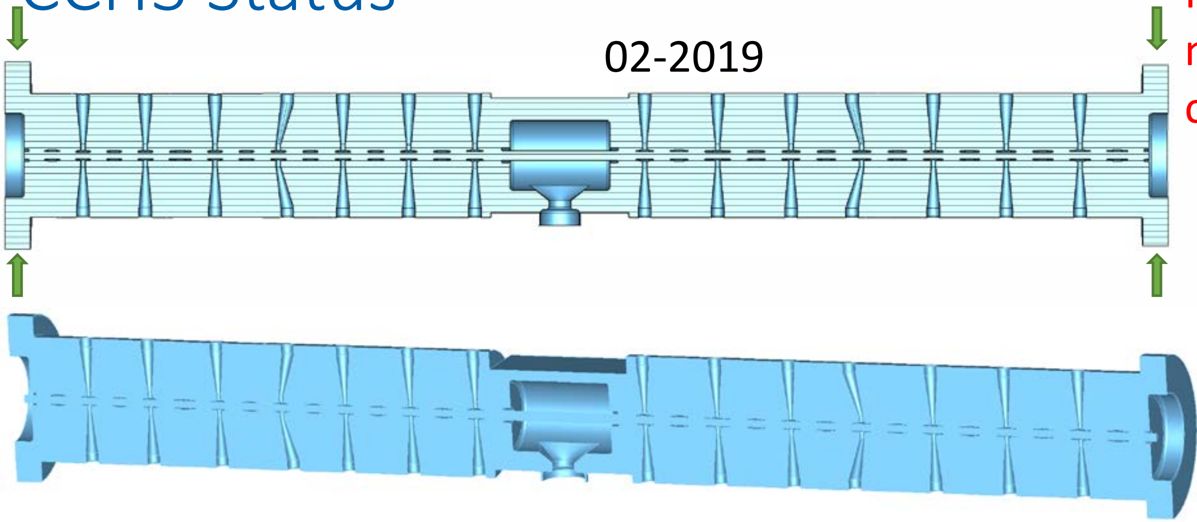
Tuning of the voltage distribution & frequency with new c-cell

New c-cell has no impact on Z_{eff}.



	Original	Final „Hi res“
$f\ [MHz]$	325	**324.3**
$Z_{eff}\ \left[\frac{M\Omega}{m}\right]$	53.2	**54.5**
ΔV_{sec1}	-	**+3.5 kV**
ΔV_{sec2}	-	**-3.5 kV**
$\Delta f_2\ [kHz]$	680	**543**

CCH3 Status

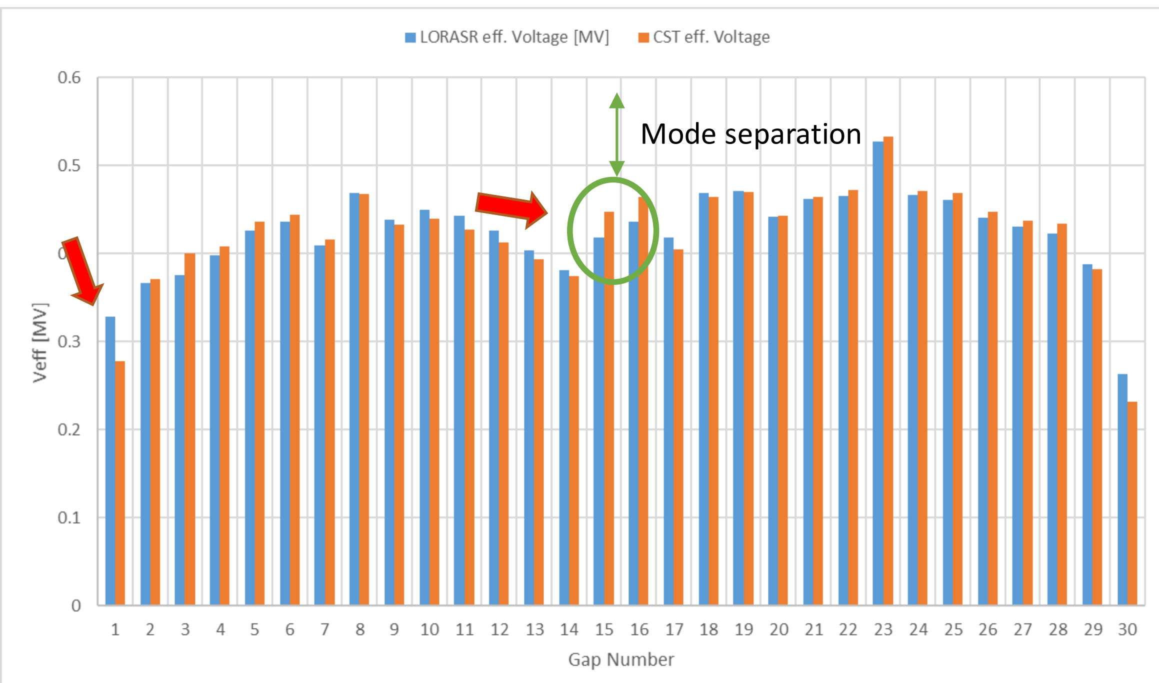


Finished and optimized to high mode separation. Reduction of end cell diameters

CCH3 end cell diameter decreased further (unified intertank design possible)

C-Cell tuning finished

Small deviation in Voltage distribution confirmed with TraceWin simulations. (up to 410 mode sep.)



	original	Final
$f\ [MHz]$	325	**324.3**
$Z_{eff}\ \left[\frac{M\Omega}{m}\right]$	46.06	**43.8**
ΔV_{sec1}	-	**-6.6 kV**
ΔV_{sec2}	-	**+6.6 kV**
$\Delta f_2\ [kHz]$	420	**367 (410)**

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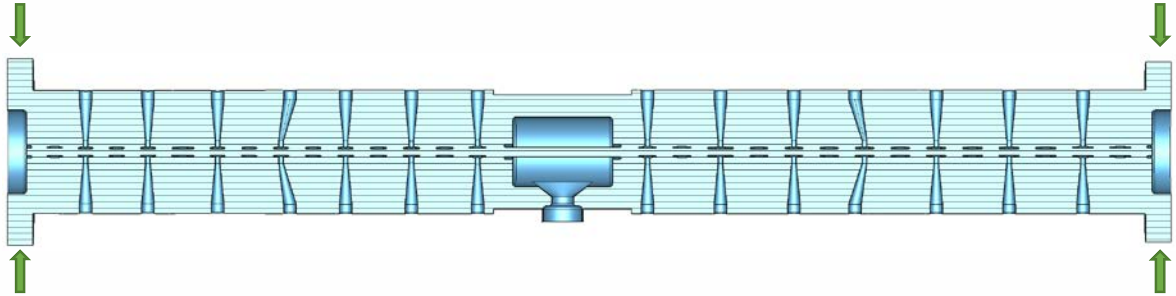
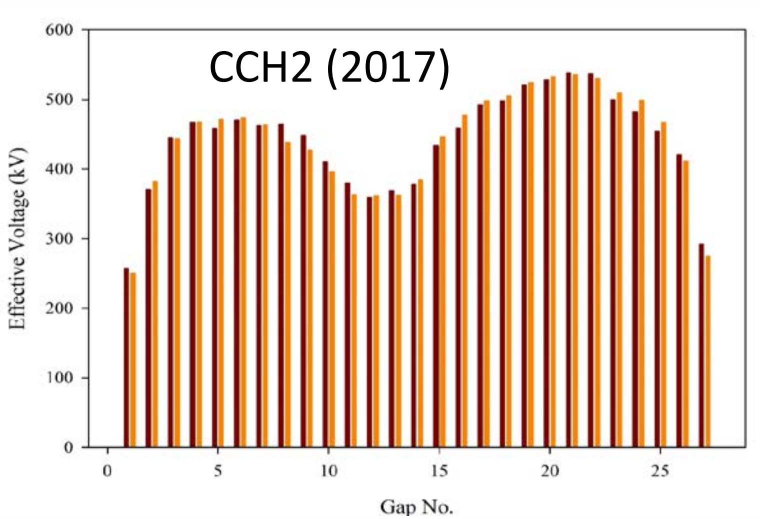
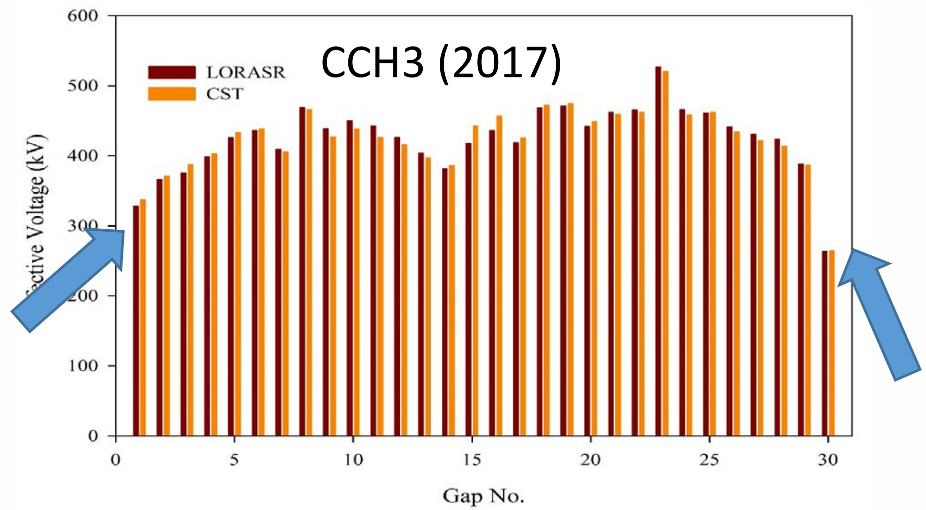
CCH3 Issues



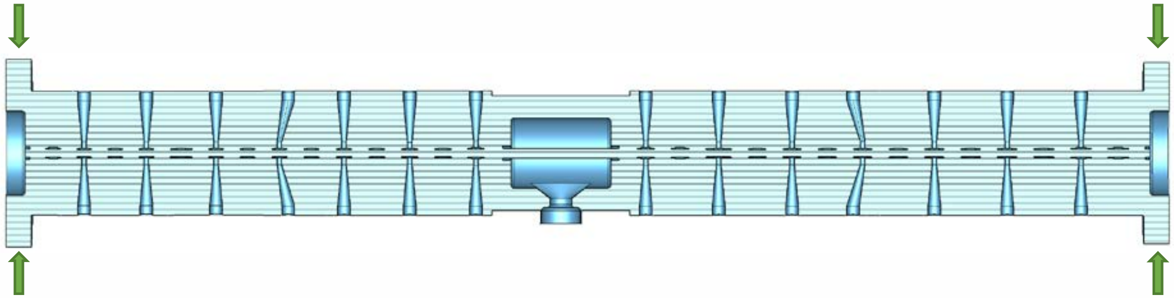
- Cavity end cells were too large for reasonable intertank design
- The voltage distribution differed from CCH1&2 significantly → why?





- Mode separation is worst in this cavity
- Tank radii were modified within the tank sections

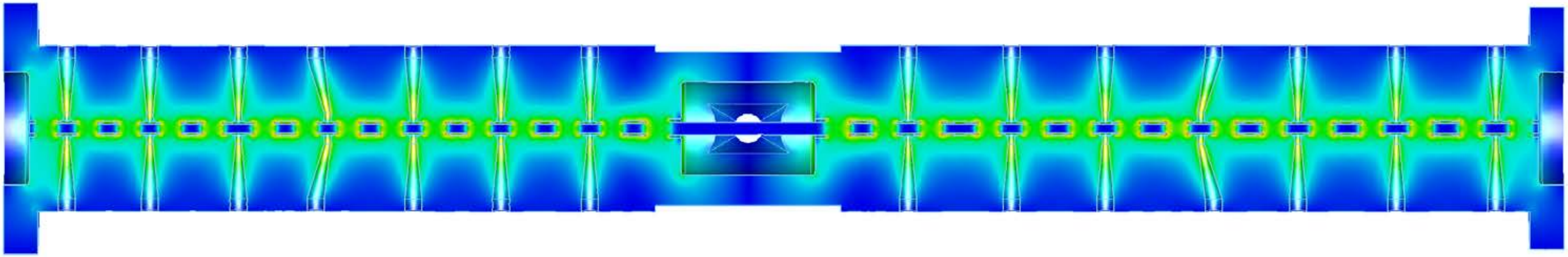
CCH3 Issues



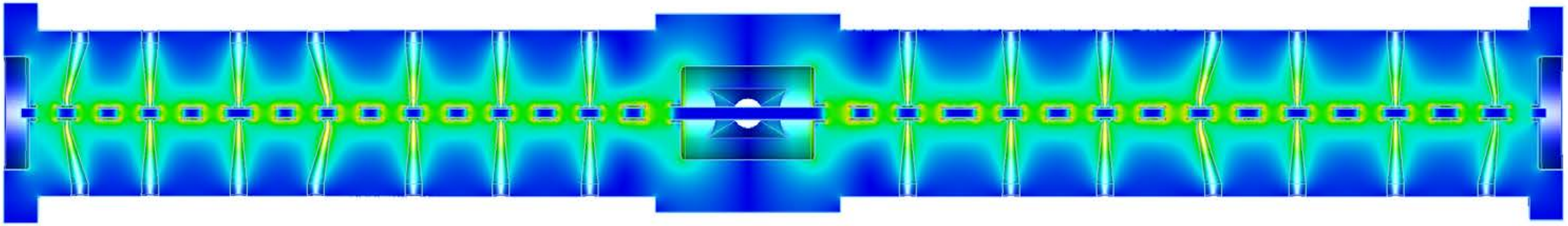
- Cavity end cells were too large for reasonable intertank design
- Only reducing the height would significantly reduce the field in the cavity ends
  - Compensate by making them wider
  - Introduce tilted stems at the ends (as in CCH1&2)
- There still was a problem at the beginning of the cavity

CCH3 Issues: Voltage Distribution

- Voltage at the beginning of the cavity was unusually high

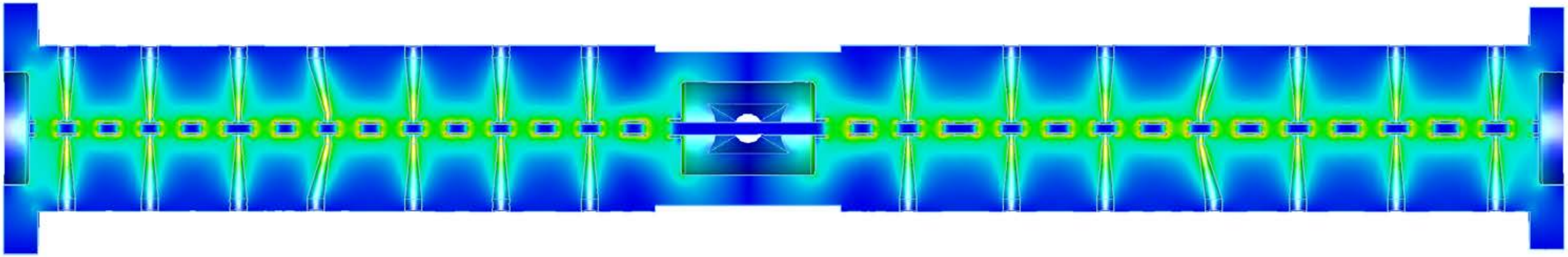


- Close distance between first stem & cavity lid
- Localized higher electric field
  - Effect is more localized than the tilted stem
  - To compensate smaller endcell height, tilted stem was inevitable

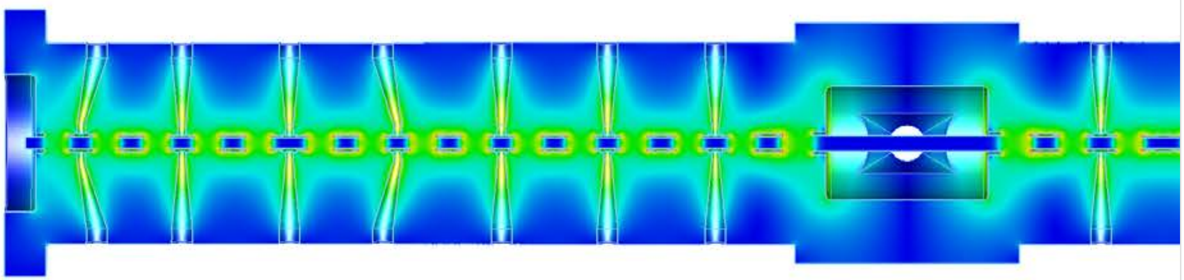


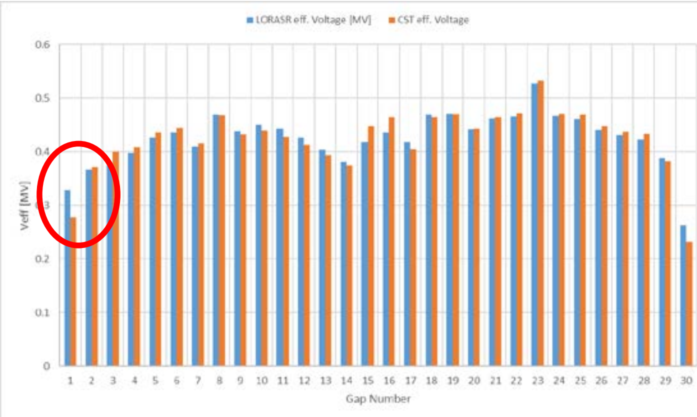
CCH3 Issues: Voltage Distribution

- Voltage at the beginning of the cavity was unusually high



- Close distance between first stem & cavity lid
- Localized higher electric field
  - Effect is more localized than the tilted stem
  - To compensate smaller endcell height, tilted s

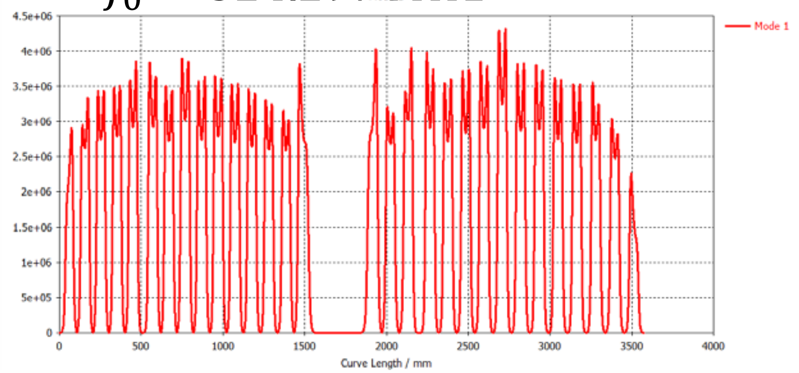




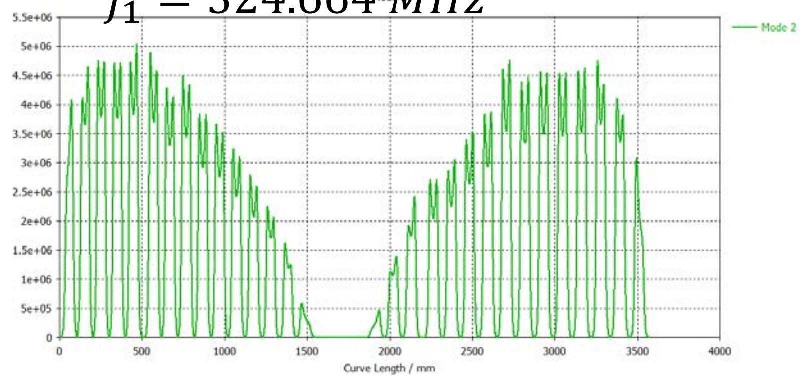
CCH3 Issues: Mode Separation

- Mode separation is difficult in CCH3

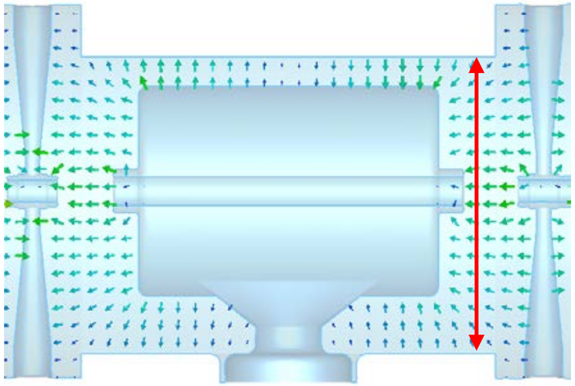
$f_0 = 324.297\ MHz$



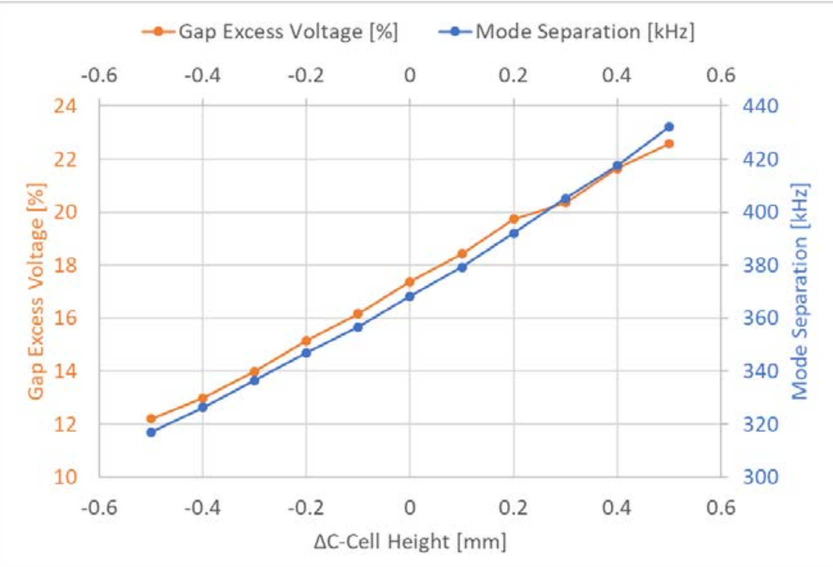
$f_1 = 324.664\ MHz$



$\Delta f = 367\ kHz$



The gap field next to the lens is dependent on the C-Cell height



The gap field next to the lens is directly tied to mode separation.

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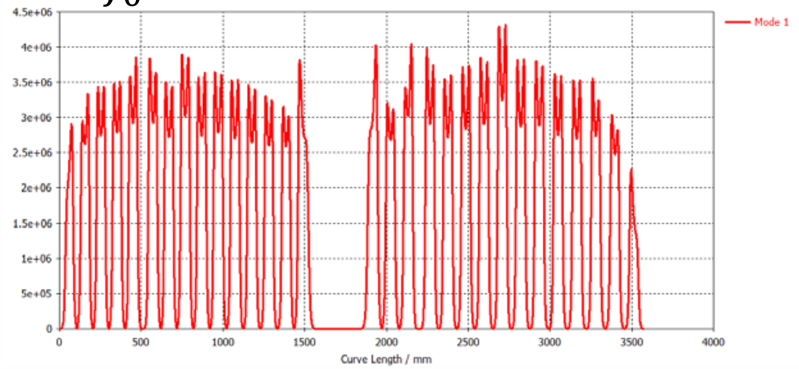
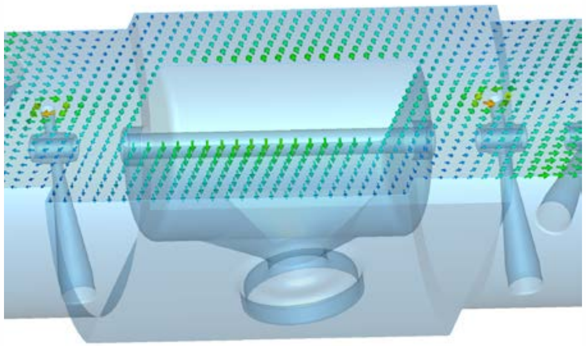
CCH3 Issues: Mode Separation

- Low field of mode 2 in C-Cell will help

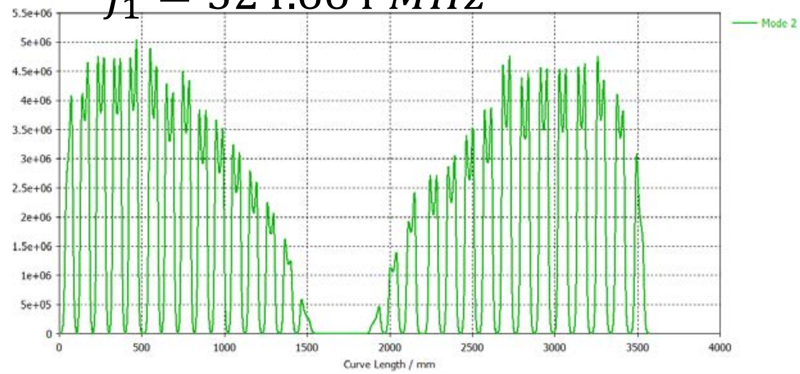
$f_0 = 324.297\ MHz$



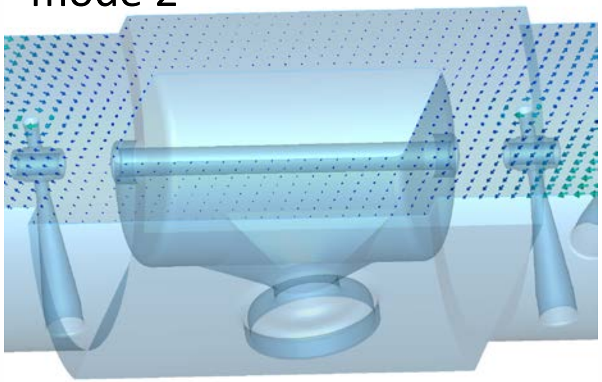
mode 1



$f_1 = 324.664\ MHz$



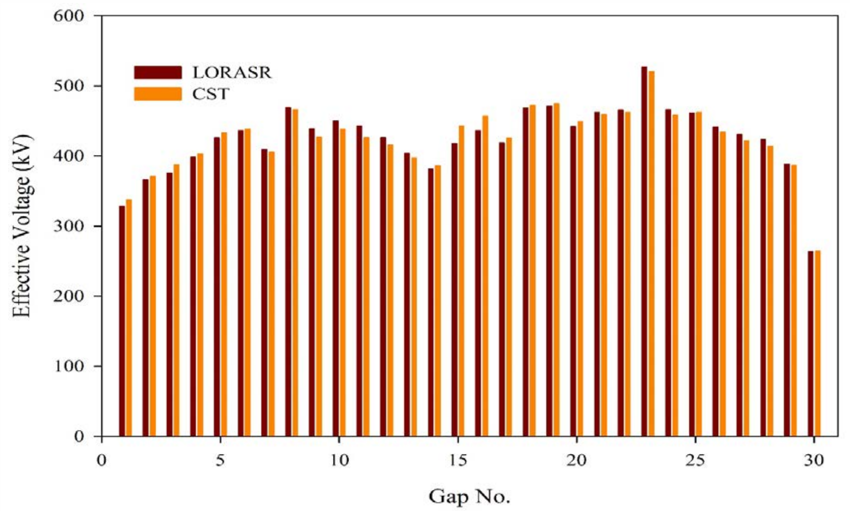
mode 2

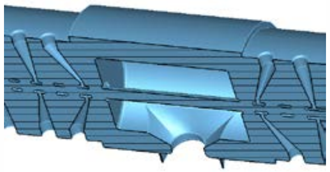


$\Delta f = 367\ kHz$

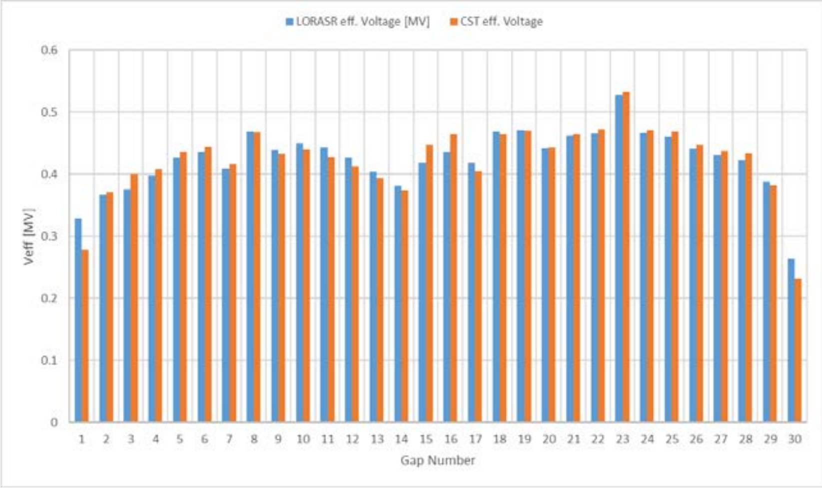
CCH3 Issues: Mode Separation

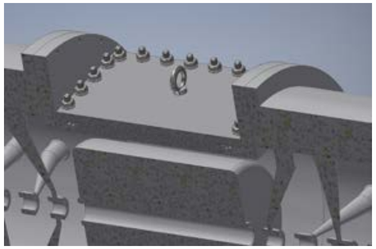
2017 – old C-Cell
$\Delta f = 680\ kHz$
(from report)
$\Delta f = 401\ kHz$
(recalculated)





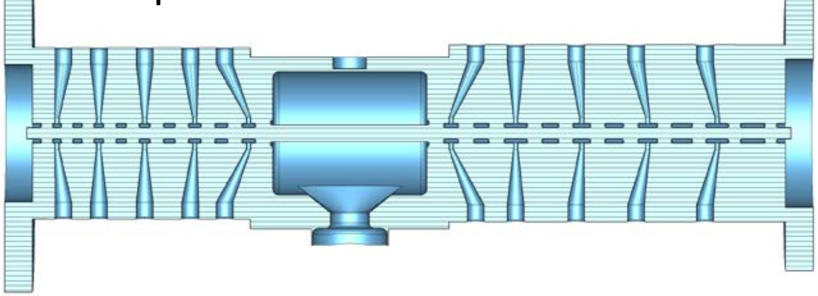
2019 – new C-Cell
$\Delta f = 367 - 410\ kHz$



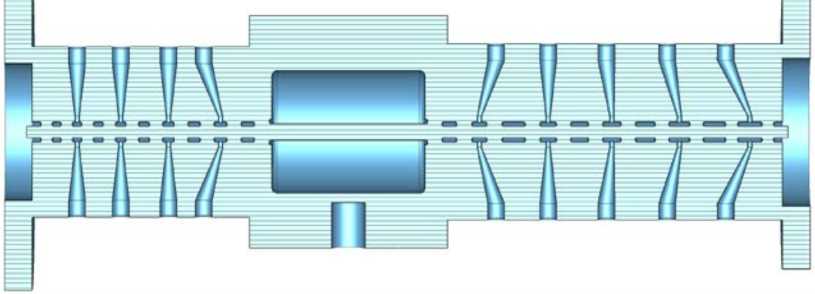


Tuning in new C-Cell geometry

Top-Tuner

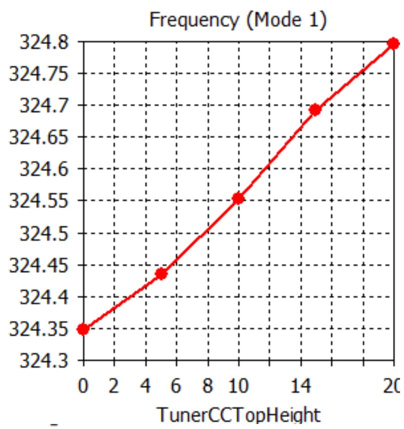


Side-Tuner

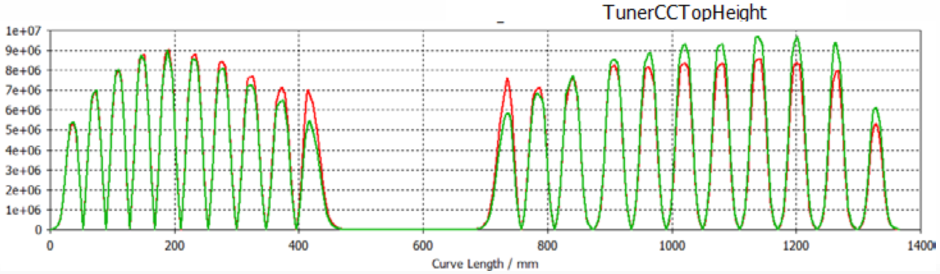


High field concentration

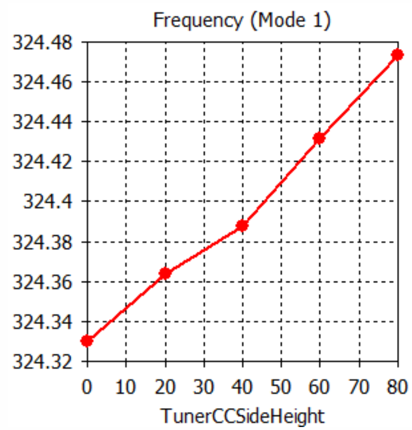
Tuning range:
$447\ kHz\ @\ 20\ mm$



Field distribution is distorted by tuner

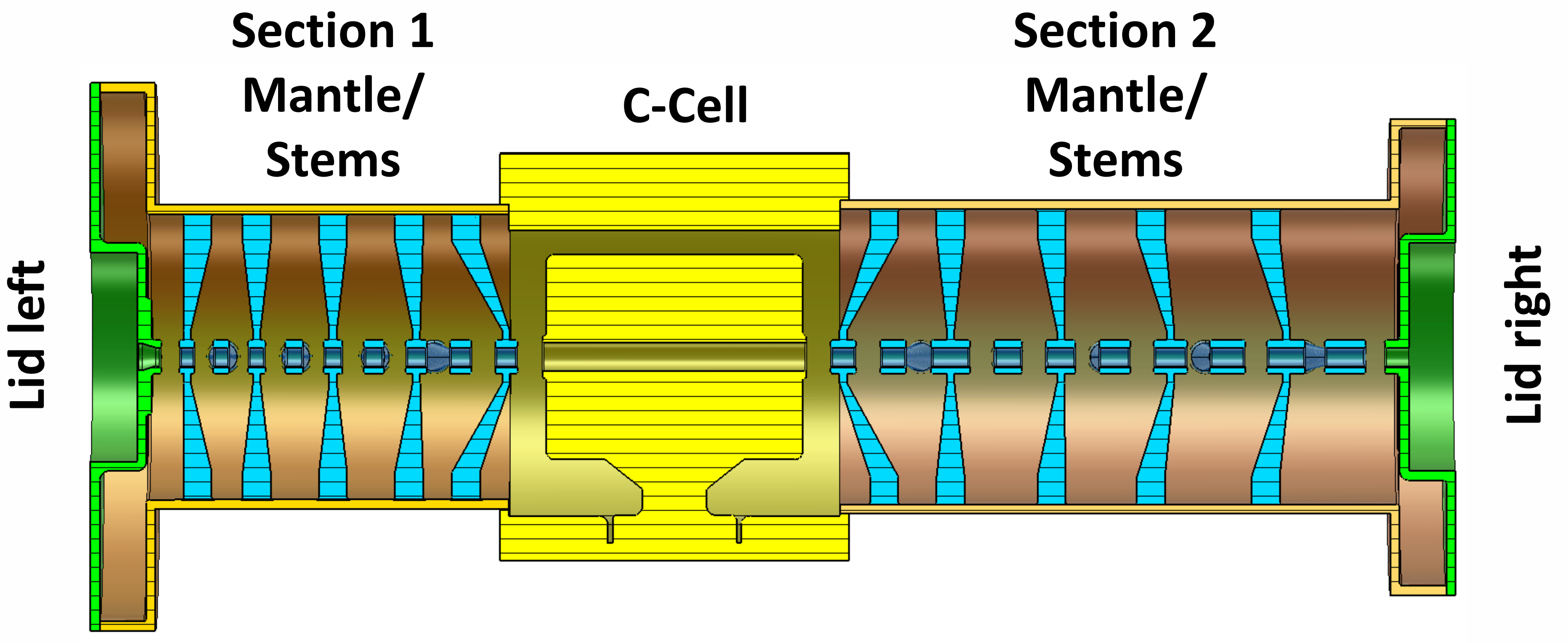


$143\ kHz\ @\ 80\ mm$



Lower impact on field distribution

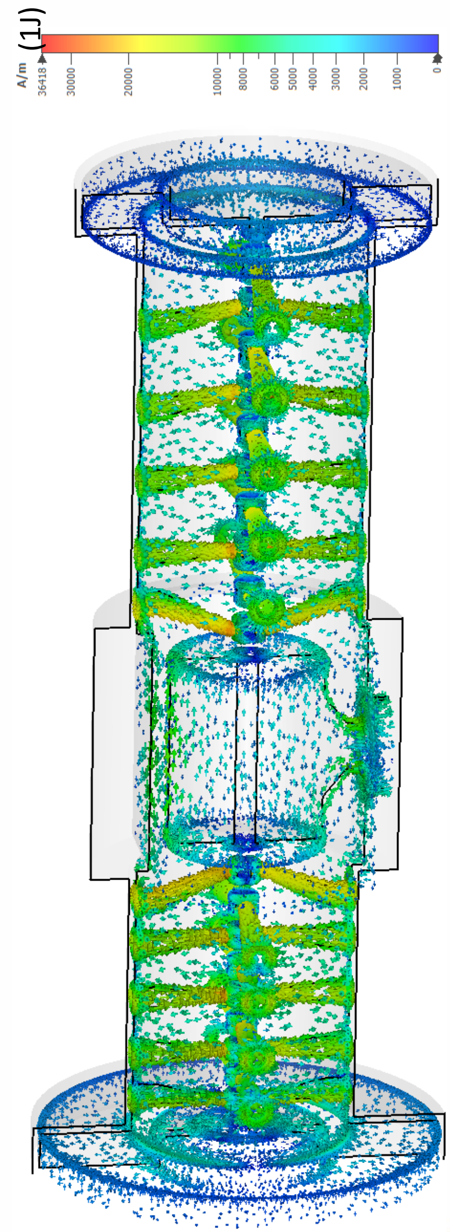
PEC Model for Power Loss Calculation



- Surface conductivity: $\sigma_{Cu} = 5.8 \cdot 10^6\, S/m$
- Total cavity voltage: $V_{eff} = 7.419\, MV$

Power Loss Calculation Results

Surface Currents



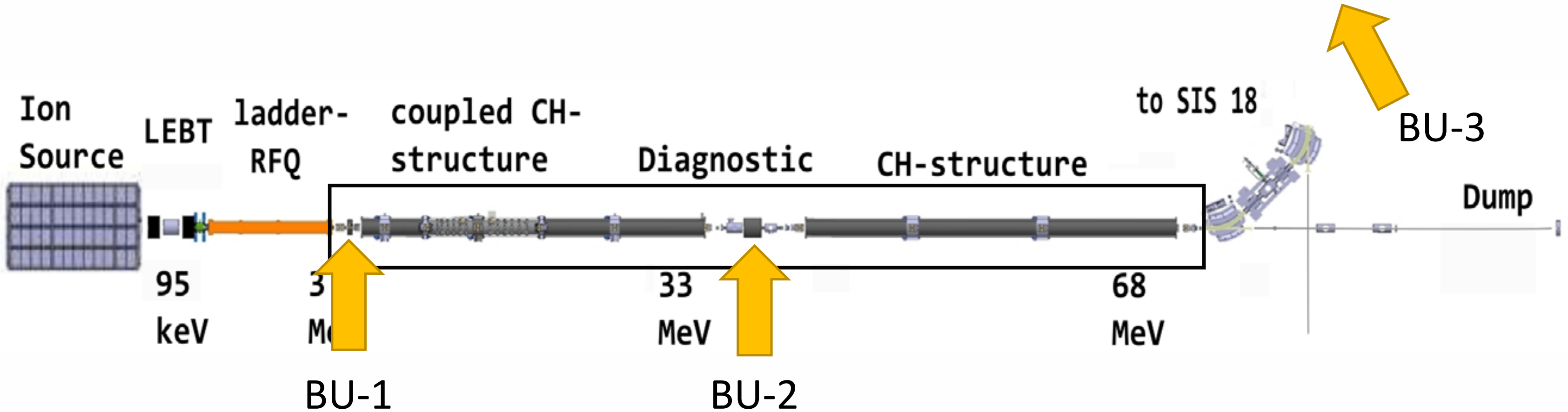
	$P_{Loss,Pulse}$ $[kW]$	$P_{Loss,Avg}$ $[W]$
Lid left	8.1	4.4
Sec 1 – Mantle	84.2	45.5
Sec 1 – Stems	193.0	104.2
Ccell	88.9	48.0
Sec 1 – Mantle	85.3	46.1
Sec 1 – Stems	240.3	129.8
Lid right	2.4	1.3
Total	**702.2 kW**	**379.2 W**

Assumed duty-cycle:

$\tau_{pulse} = 100\ \mu s, f_{rep} = 2.7\ Hz \rightarrow$ duty cycle $= 5.4 \cdot 10^{-4}$

Buncher Cavities

Buncher Overview



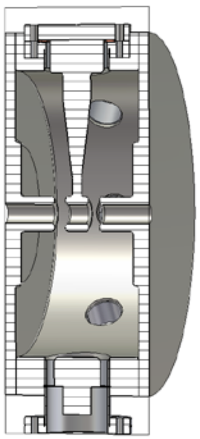
pLinac has 3 buncher cavities

@ 3 MeV, 33 MeV & 68 MeV

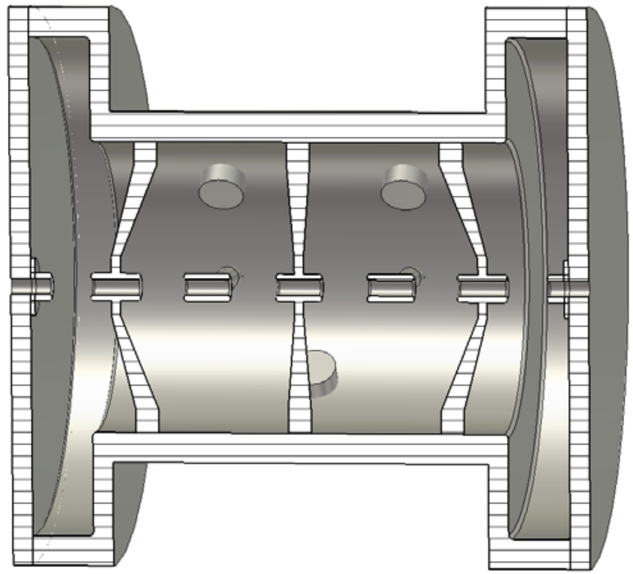
1. Matching RFQ to CH-DTL
2. Diagnostics matching to CH-DTL
3. Debuncher for SIS18 Injection

- Each buncher has to be optimized for its purpose
- Power requirements range from 11 kW to 200 kW

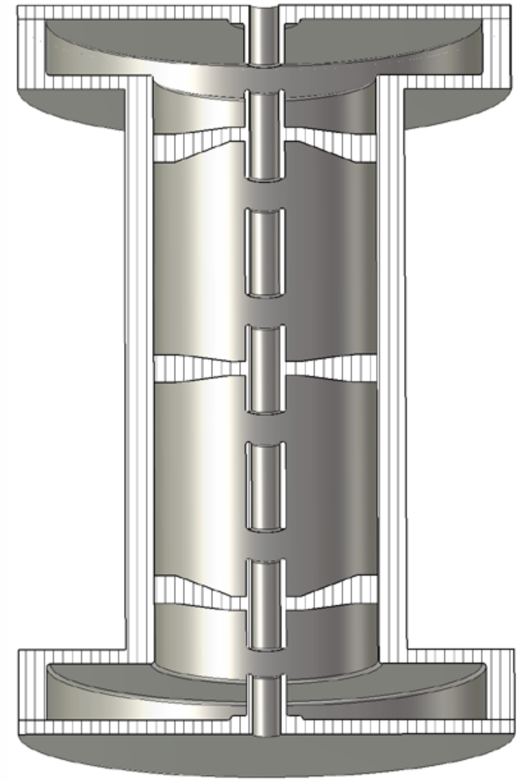
Buncher Design



finished



final details



details

MEBT Buncher:

- Short design, fits MEBT
- “Spiral” design superior to CH/single spoke
- Bulge for QT1 connection
  - Repeated on the right for symmetry only

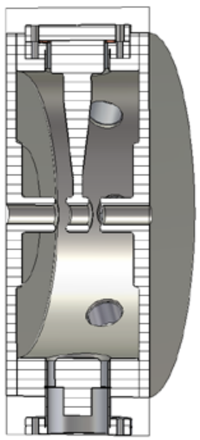
DIAG Buncher:

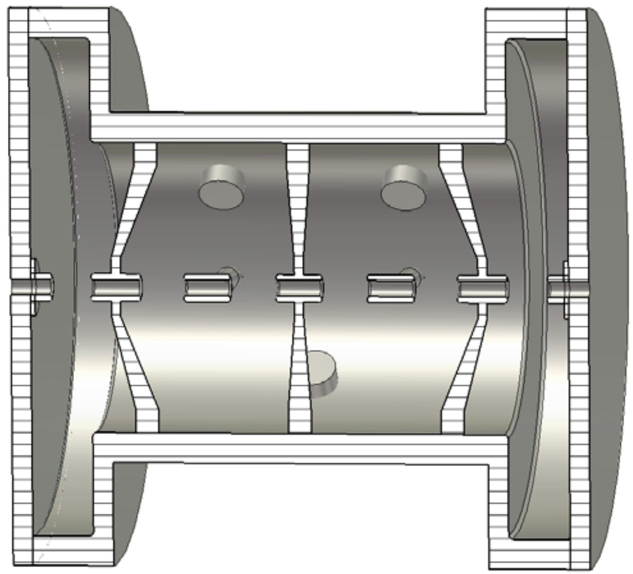
- Optimized geometry:
  - Short, high Shunt impedance
  - Flat field distribution
- Stem design similar to CCH/CH

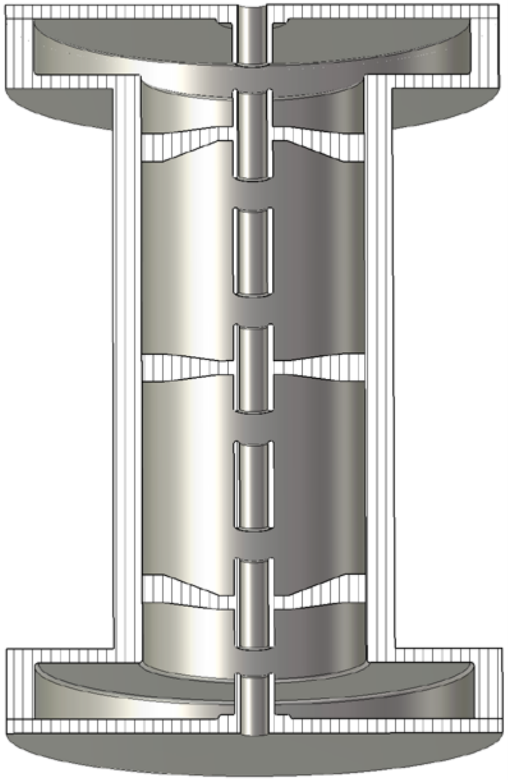
DeBuncher:

- Optimized geometry:
  - Short, high Shunt impedance
  - Flat field distribution
- Stem design similar to CCH/CH

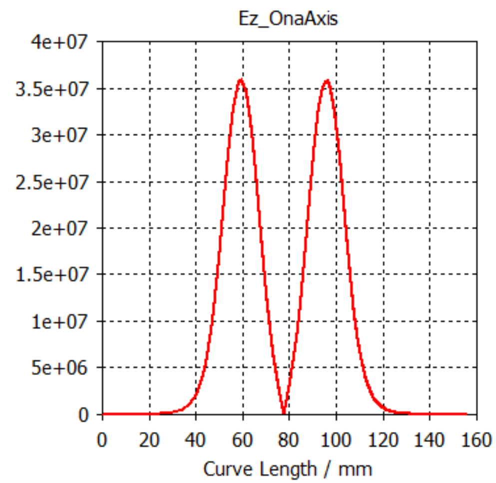
Buncher Design



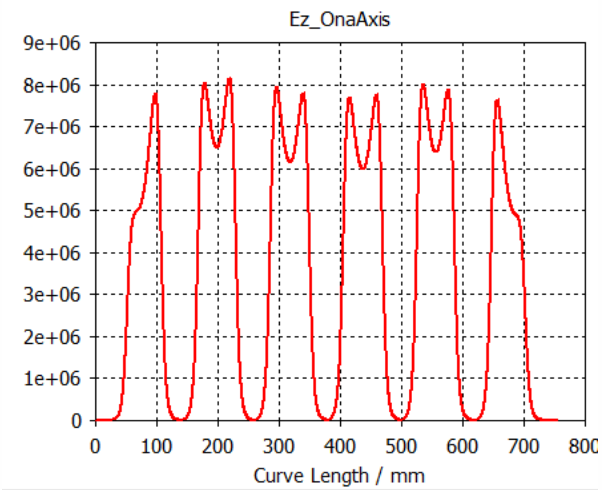




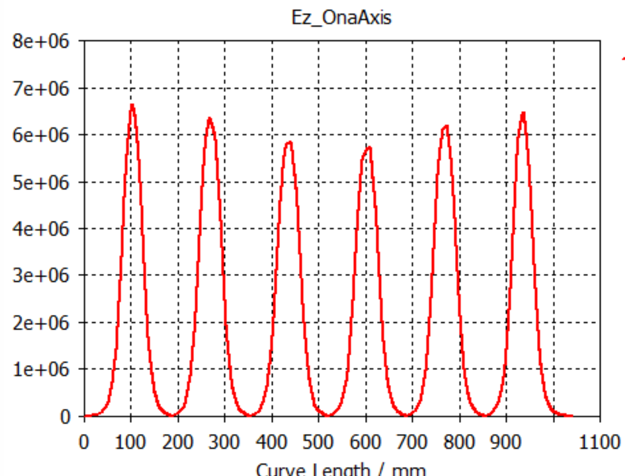
finished



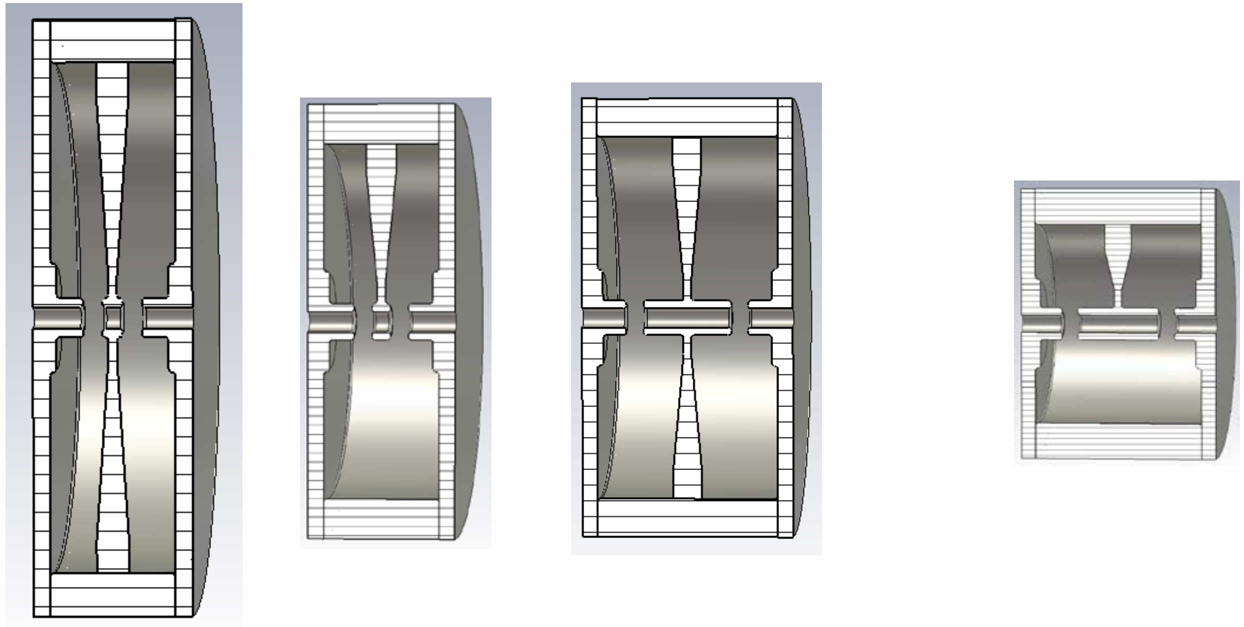
final details



details



MEBT Buncher considerations*



	“CH”-Type	“Spiral”-Type	“CH”-$3\beta\lambda/2$	“Spiral”-$3\beta\lambda/2$
R_{inner}	$235.7\ mm$	$177.5\ mm$	$188.9\ mm$	$112\ mm$
L_{outer}	$148\ mm$	$148\ mm$	$221.3\ mm$	$221.3\ mm$
$f_{res}\ [MHz]$	324.404	324.124	324.189	323.9
$Z_{eff}\ [M\Omega/m]$	26.8	42.35	19.7	17.7
$P_{loss}(CST)$	$15.6\ kW$	$9.85\ kW$	$13\ kW$	$14.47\ kW$
$E_{max}[kilp]$	1.05	1.14	0.25	0.86

*values at time of comparison, changes were made during final design

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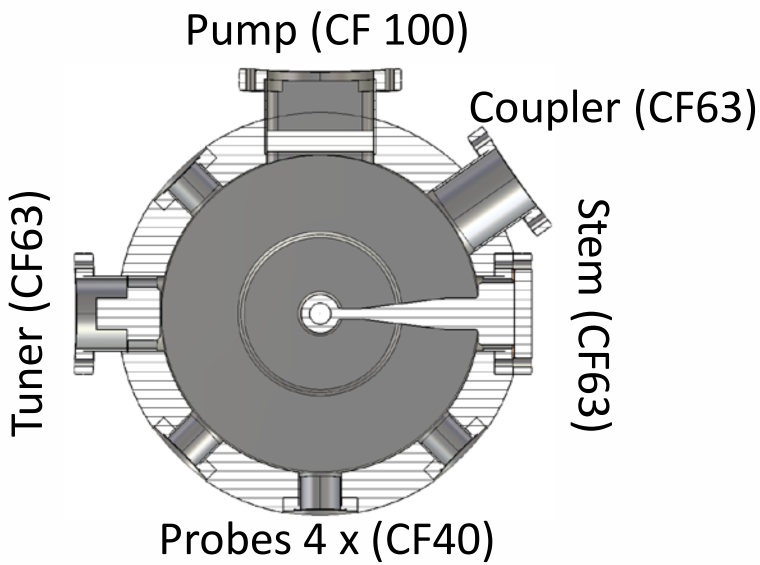
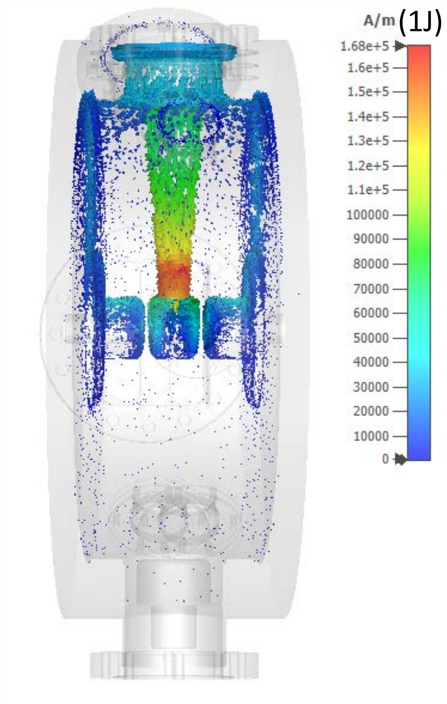
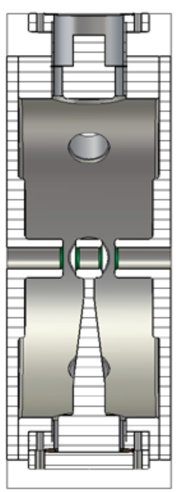
MEBT Buncher + Power Loss

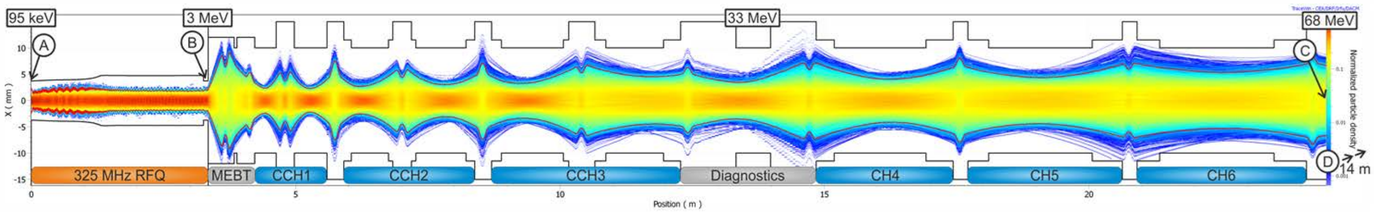


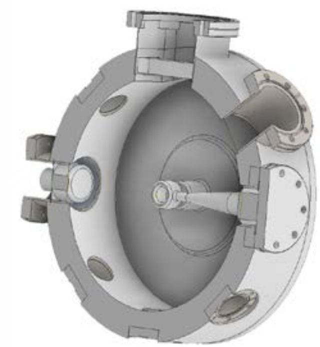


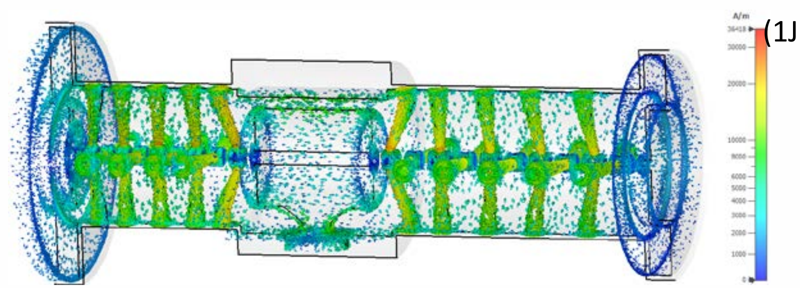


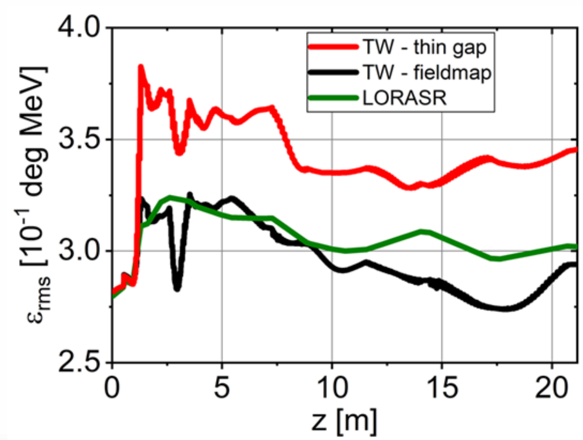
	Lid left	Shell	Lid right	Stem	Total
$P_{Loss,Pulse}\ [kW]$	0.756	1.703	0.756	8.613	**11.86**
$P_{Loss,Avg}\ [W]$	0.41	0.92	0.41	4.65	**6.4**
Assumed duty-cycle: $\tau_{pulse} = 100\ \mu s$, $f_{rep} = 2.7\ Hz$ → duty cycle $= 5.4 \cdot 10^{-4}$					

That’s it & thanks to the whole pLinac team









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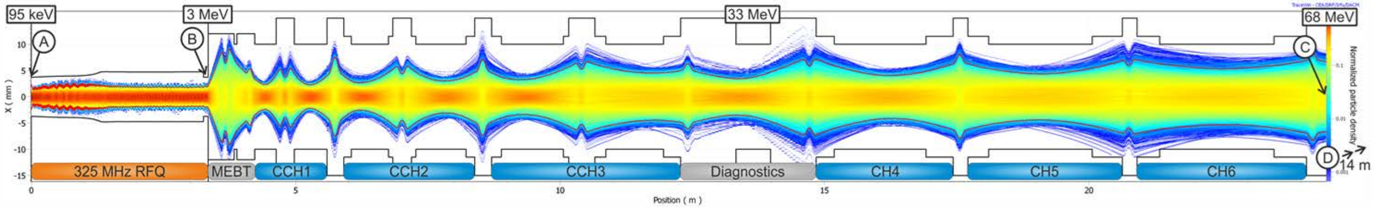

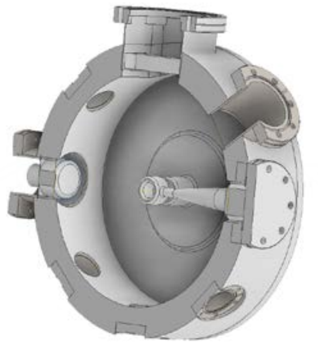

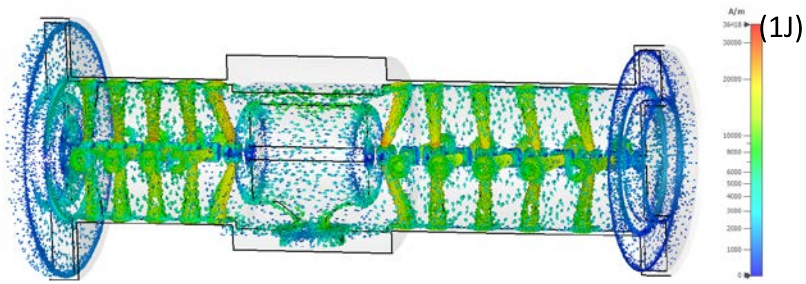

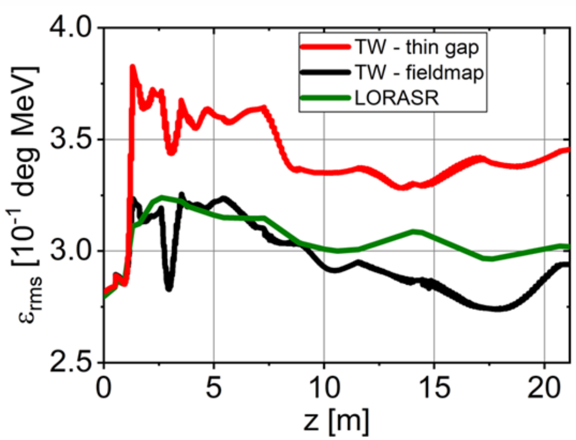

Any questions, you have?

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