Low-β high gradient S-band accelerating structure for hadron therapy linacs*

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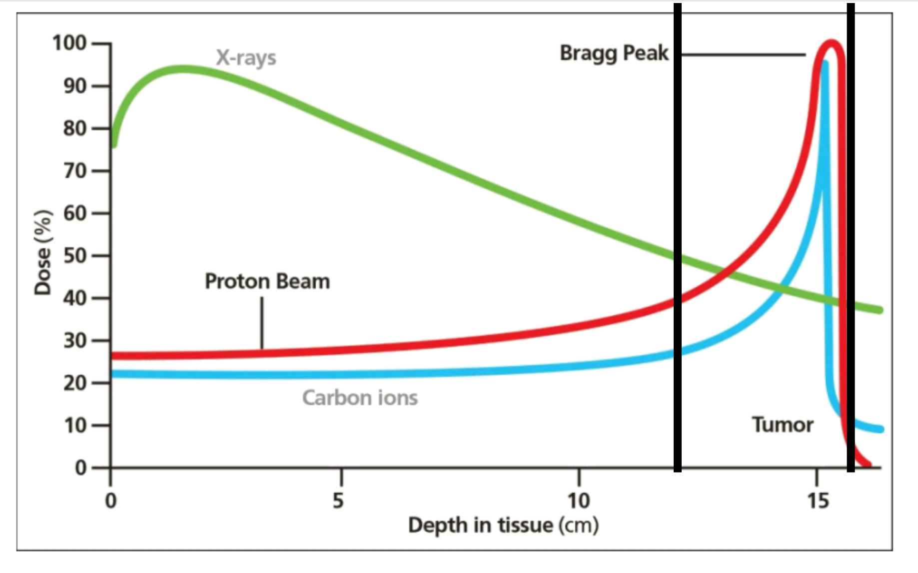
Content

- Proton and carbon therapy
- Advanced Compact Carbon Ion Linac
- High gradient limits
- Accelerating structure for β=0.5-0.7
- Accelerating structure for β=0.43
- Accelerating structure for β=0.3
- Conclusions

X-ray and ion therapy

- Conventional compact photon therapy linacs deliver a significant amount of dose outside the tumor region
- High-energy protons and heavy ions physical depth-dose distribution in tissue is characterized by a small entrance dose and a distinct maximum (Bragg peak)
- For particles the dose before the tumor is ~50% less that at the tumor region
- Carbon ions have much narrower Bragg peak comparing to protons ~ 3 times higher efficiency
- Carbon ions ~35% better treat “radioresistant” hypoxic cells than protons, have higher Radio-Biological Efficiency
- Lower scattering before the tumor for carbons

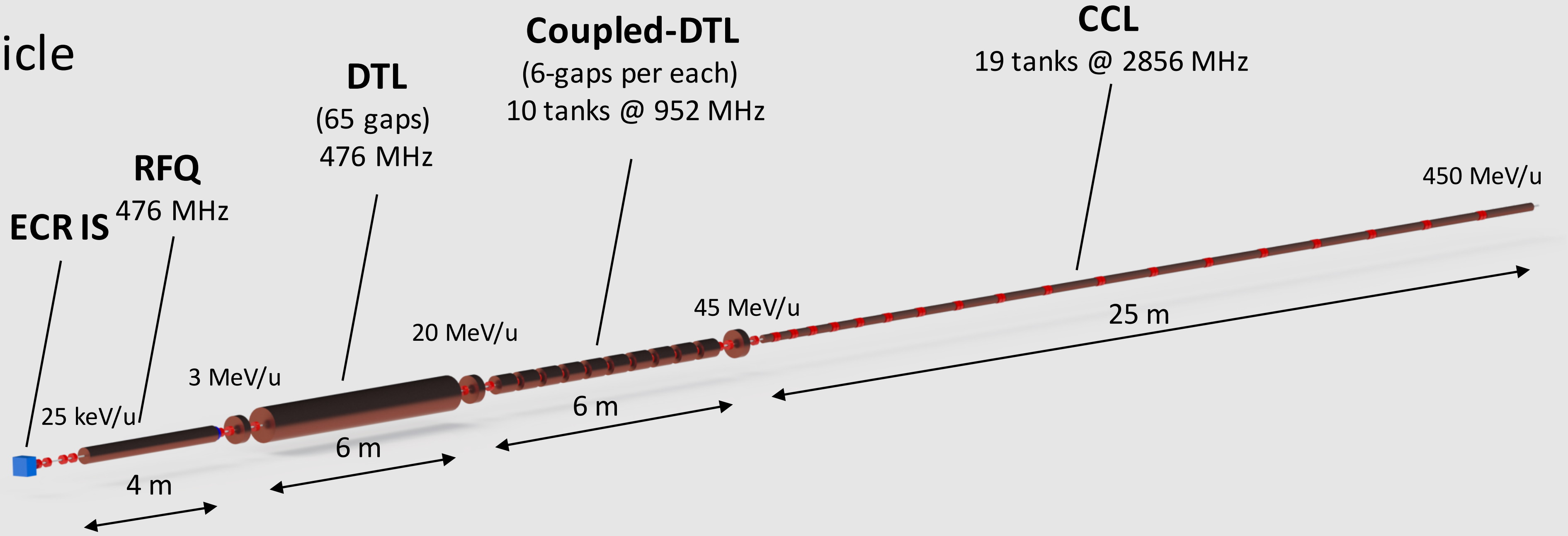


Accelerators for hadron therapy

	Cyclotron	Synchrotron	Linac
Particles	p or C	p, C	p, C
Variable energy	With degrader	From pulse to pulse without losses	From pulse to pulse without losses
Beam quality	Bad quality due to beam energy degrader	Good	Good
Repetition rate	CW	< 1 Hz	< 300 Hz
Compactness	Best	Good	Depends on gradient

Advanced Carbon Ion Linac (ACCIL)

- 200-250 MeV for protons and 400-450 MeV/u for $^{12}C^{5+}$ in order to penetrate up to 30 cm inside the human tissue
- Total linac length 45 m with 50 MV/m accelerating gradient at S-band
- 500 ns pulse at 120 Hz rep. rate
- 10^{10} protons/second (27μA current) and 10^{9} ions/second (13.4μA particle current) intensity
- Beam average particle current
  - 1.62 nA - protons
  - 0.8 nA - $^{12}C^{5+}$



High gradient limits

Maximum surface electric field

A reliable surface field in structures with nose cones is <160 MV/m (experienced in RF guns and Side Coupled linacs)

Pulsed heating

$$\Delta T = \frac{H_{max}{}^2 \sqrt{t_{pulse}}}{\sigma\delta\sqrt{\pi\rho' c_\varepsilon k}}$$

for annealed copper
ΔTmax=50 K

where ΔT – is the pulsed heating value [K], H_{max} – maximum surface magnetic field [MA/m] and t_{pulse} – is the total pulse length including transient processes [μs]. σ – electrical conductivity, δ-skin depth, ρ'- density, c_ε- specific heat, k – thermal conductivity of the metal.

Modified Poynting vector

$$S_c = Re\{\overline{S}\} + \frac{Im\{\overline{S}\}}{6}$$

For 1.5 μs pulse length and S band the limit is ~2.8 MW/mm^2 (10^-6 bpp/m breakdown rate).* This parameter hasn't been confirmed for S-band linacs yet, but we will keep all 3 breakdown parameters below limits.

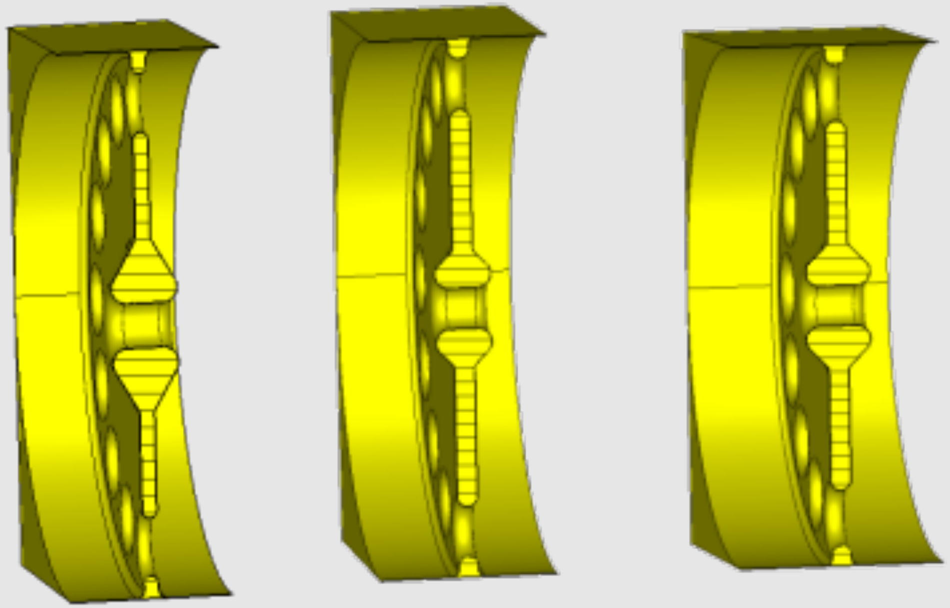
**A. Grudiev et al. RF design of a novel S-band backward traveling wave linac for proton therapy, Proceedings LINAC'14*

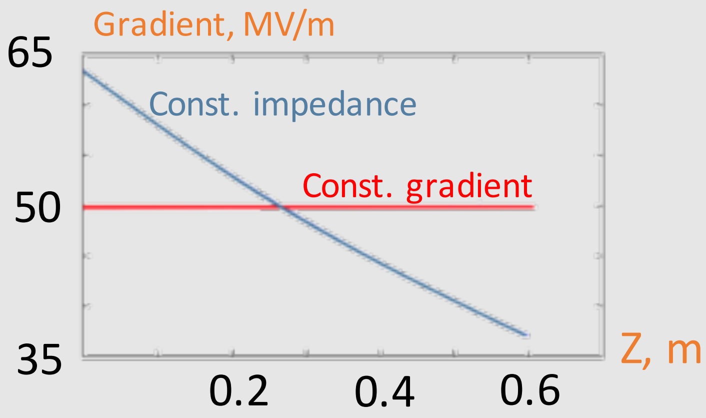
β=0.3-0.7 accelerating structures. Main goals

- 19 accelerating tanks with fixed phase velocities
- Accelerating gradient 50 MV/m
- S-band
- Pulse flat-top 500 ns
- Rep. frequency 120 Hz
- Consider standing and traveling wave structures

β=0.5-0.7 Traveling wave structures

- Disk-loaded waveguide based structure with magnetic coupling is used
- Constant gradient is chosen
- One can control group velocity along the linac keeping aperture radius constant
- There is pulsed heating at magnetic coupling spots

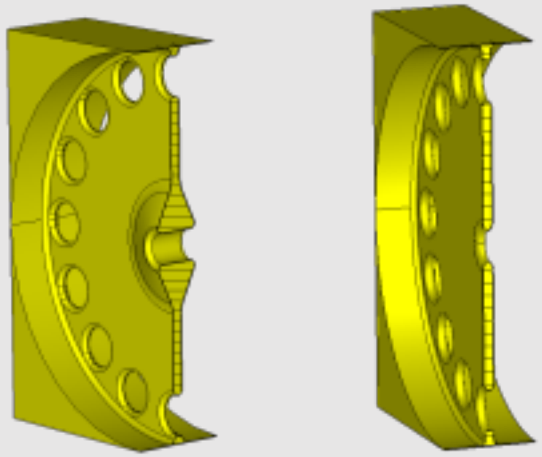




β	0.5	0.6	0.7
Shunt impedance, MOhm/m	56	58	67
Filling time, ns	1000	1000	1500
$P_{in\ peak}$, MW	40	54	54

β=0.43 Traveling wave structure

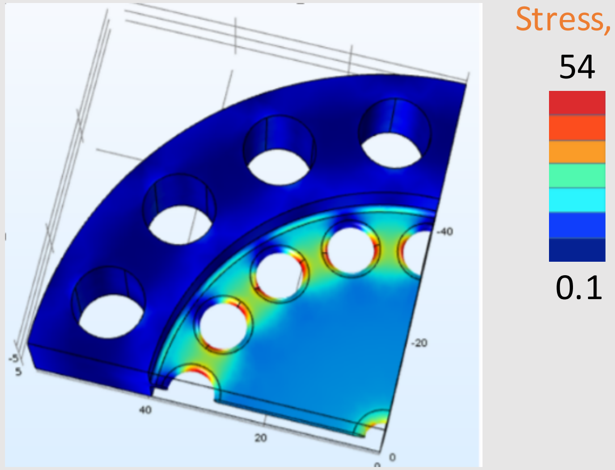
- Although noses increase shunt impedance, surface E field is at the breakdown limit level



ΔF=-0.316 MHz

Iris thickness 2 → 4 mm

Stress 81 → 54 MPa

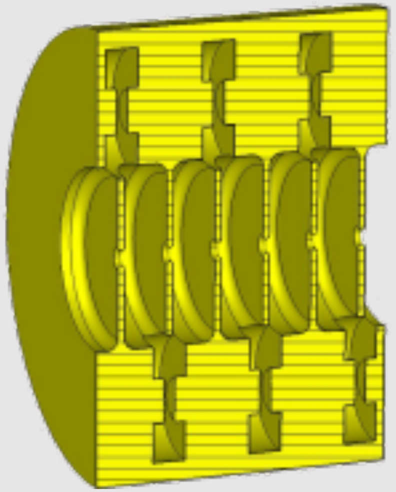


	Noses 🔴	No noses 🟢
Mode	5π/6	5π/6
Eacc, MV/m	50	50
Emax, MV/m	200	90
Shunt impedance, MOhm/m	51	36
Group velocity, %	0.4	0.4
Pulsed Heating, K (limit 50)	11	18
<Sc>, MW/mm^2 (limit ~2.8)	0.7	1.3

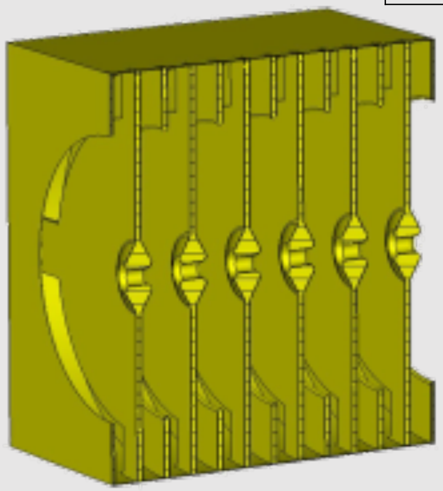
β=0.43 Standing wave geometries

- Biperiodic (BPS), Side coupled (SCL) and Disks and Washers (DAW) compensated structures were compared to BTW
- BTW shows higher shunt impedance at lower peak fields
- BTW filling time is lower

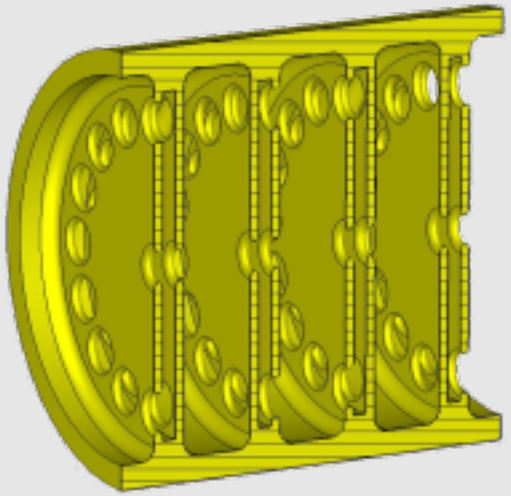
Structure type	BPS	BTW
Coupling, %	4.6	
Shunt impedance, MOhm/m	32	36
Eacc, MV/m	50	50
Emax, MV/m	112	90
Pulsed Heating, K (limit 50)	15.7	18
<Sc>, MW/mm^2 (limit ~2.8)	1.35	1.3
100% filling time, ns	1500	1000
Power (20 cells, 50 MV/m), MW	35.5	30



Side Coupled



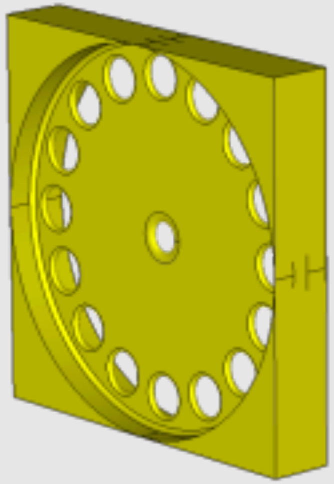
Disks and Washers

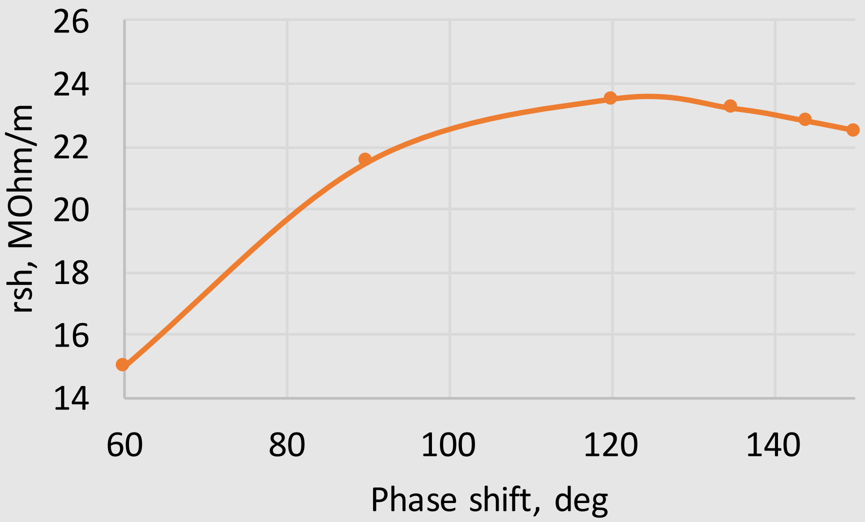


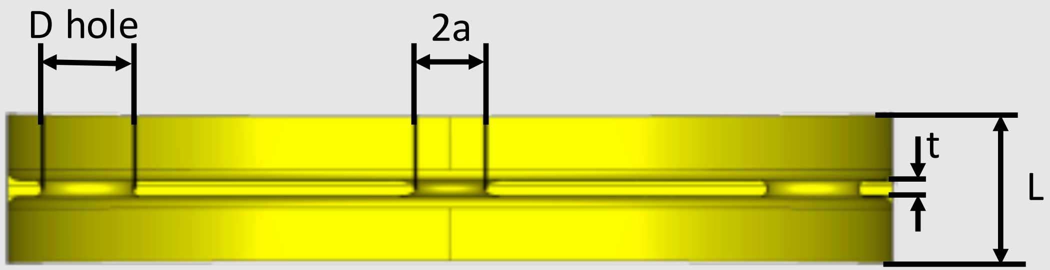
Biperiodic

β=0.3 BTW

- Accelerating cell length is too small to consider BPS => BTW is chosen
- Highest shunt impedance is at 2π/3 mode
- Cell length is too small -> needs to be increased







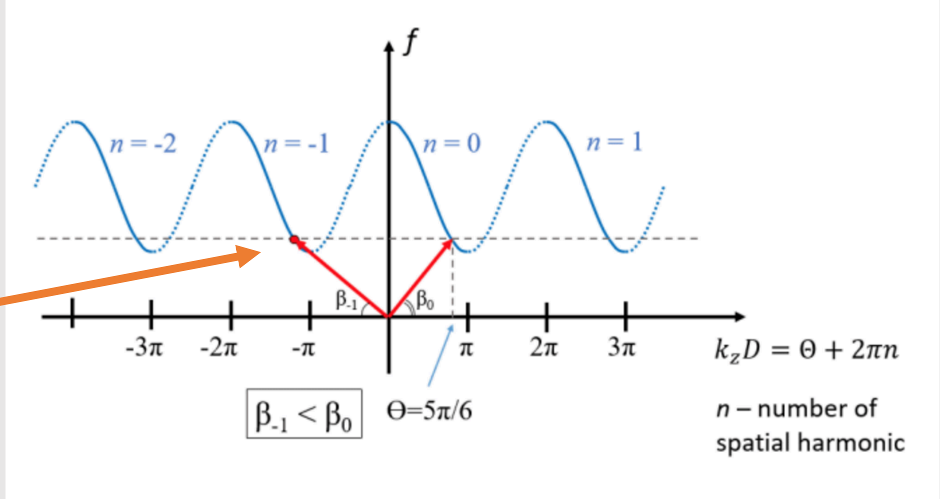
θ=2π/3, 50 MV/m

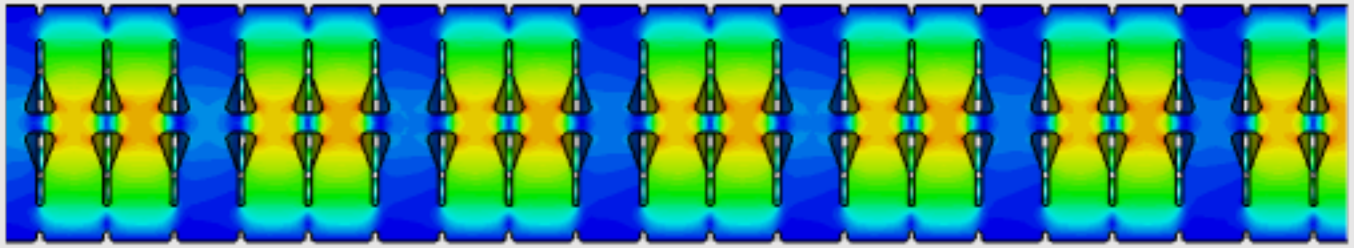
Parameter	Value
D hole, mm	8
a ,mm	3
t, mm	1.5
L, mm	10.5
Shunt impedance, MOhm/m	23.5
Emax, MV/m	112.5
Pulsed Heating, K	33
<Sc>, MW/mm^2	1.7

Spatial harmonics

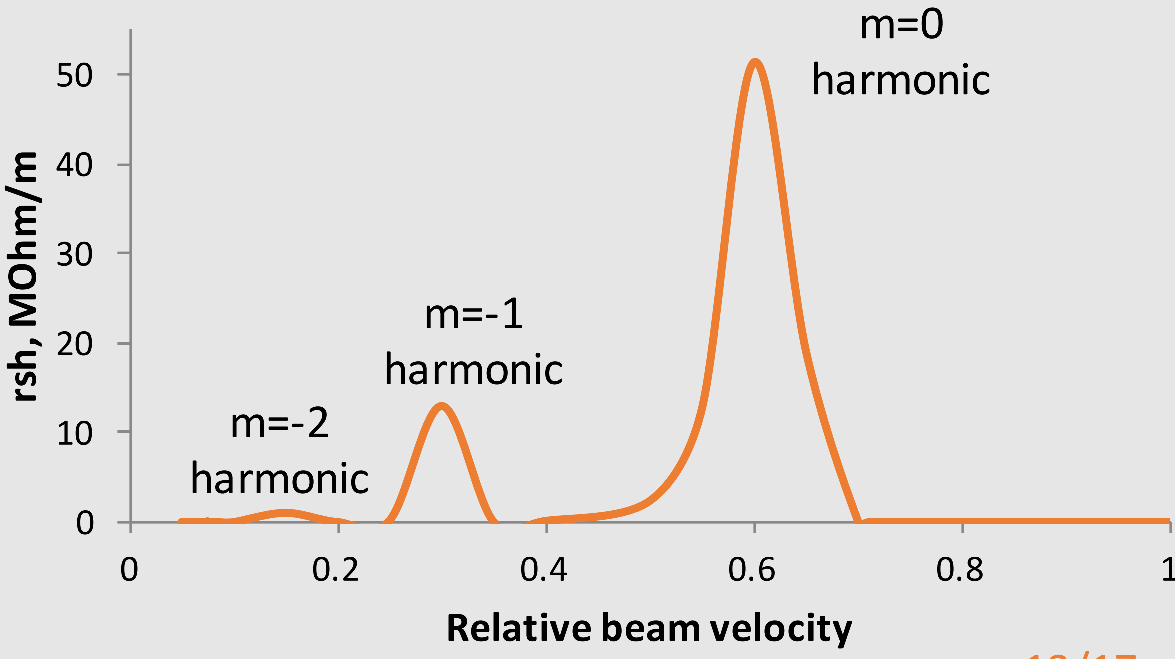
- There is an infinite number of spatial harmonics for periodic structures
- Accelerating cell length $L = \frac{\beta\lambda(\theta \pm m\pi)}{2\pi}$

We want to operate at spatial harm. -1





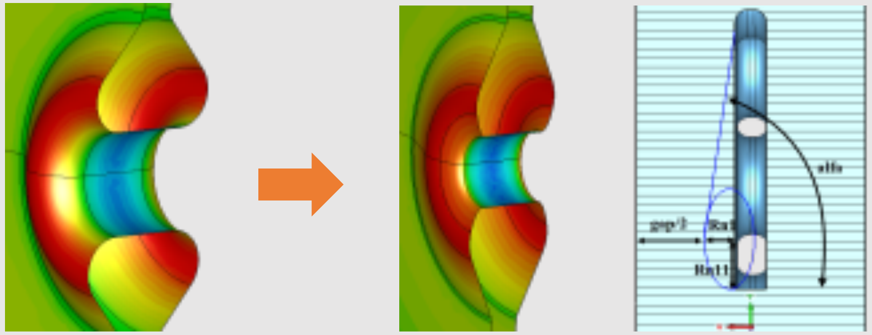
- After the change of the spatial harmonic, group velocity remains the same
- Length (m=-1)=21 mm for θ=5π/6
- With 21 mm cell length there is a room for noses

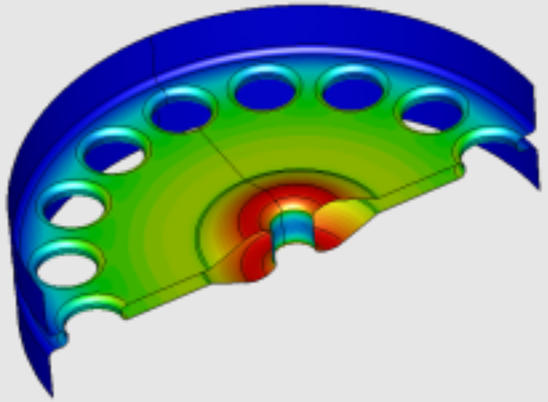


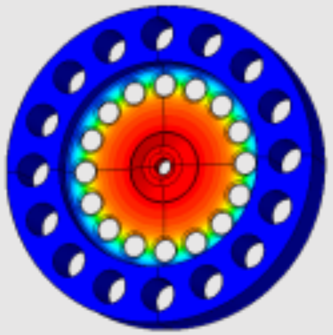
β=0.3 BTW at -1 spatial harmonic

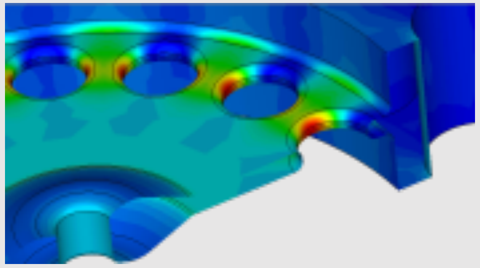
- 5π/6 mode allows to achieve the highest shunt impedance at -1 spatial harmonic
- In the longer structure noses can be introduced to increase shunt impedance
- Elliptical noses profile allows to decrease the maximum surface fields

	m=0, 2π/3	m=-1, 5π/6, no noses	m=-1, 5π/6, noses
t, mm	2	3	2.5
<Sc>, MW/mm^2	1.4	2.03	1.3
Pulsed heating, K	24	33.46	28.2
Emax, MV/m	92.5	130	156.5
Shunt impedance, MOhm/m	22	18.58	31.7
ΔT, C (22C ambient)	39.2	21.2	15.6
Von Mises stress, MPa	57	75	59.6
Length, mm	10.5	21	21









Conclusions

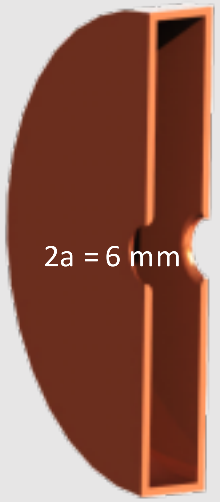
- Carbon ion therapy is more efficient than X-ray and have higher Radio Biological Efficiency
- Treatment with linacs is more efficient than with cyclotrons and synchrotrons due to the better beam quality and faster energy variation
- Argonne National Laboratory and RadiaBeam Systems developed an Advanced Compact Carbon Ion Linac, which accelerates carbon ions up to 450 MeV/u at 45 m length
- S-band accelerating structures were developed for both protons and carbon ions acceleration in the velocity range β=0.3..0.7
- BTW and BPS for β=0.43 were designed to satisfy requirements of a compact carbon ion linac
- For β=0.3 a BTW accelerating structure was designed to operate at -1 spatial harmonic
- An advantage of using a -1 spatial harmonic for very low betas over the fundamental spatial harmonic is shown

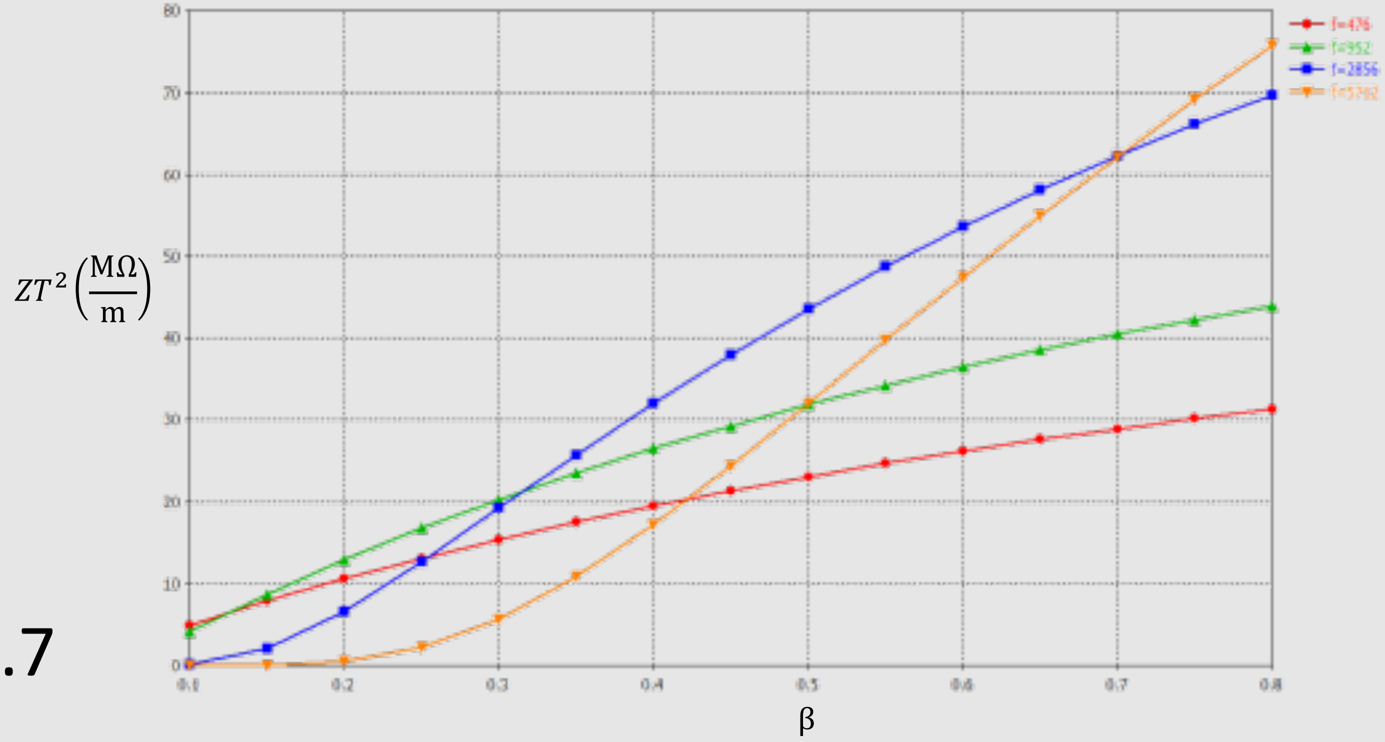
References

- P.N. Ostroumov et al. ,Compact Carbon Ion Linac, Proceedings of Na-PAC 2016, Chicago, IL, USA
- A. Plastun et al., Beam Dynamics Studies for a Compact Carbon Ion Linac for Therapy, Proceedings of LINAC 2016, East-Lansing, MI, USA
- S.V. Kutsaev et al., High Gradient Accelerating Structures for Carbon Therapy Linac, Proceedings of LINAC 2016, East-Lansing, MI, USA

Accelerating efficiency. Transit time factor

- S-band was chosen for high gradient section, because it was proven to sustain 50 MV/m*
- Pillbox cavity – typical S-band structure





  - S-band in pillbox has the highest efficiency at β=0.3-0.7

*S.V. Kutsaev et al., High Gradient Accelerating Structures for Carbon Therapy Linac, Proceedings of LINAC 2016, East-Lansing, MI, USA