SSR2 RF design

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FNAL-IBS Workshop

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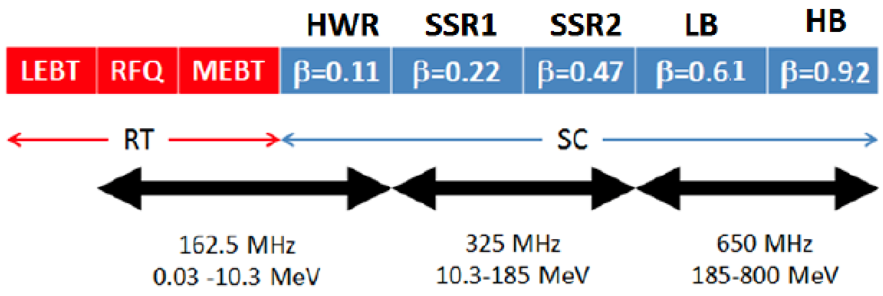
Outline

- SSR2 as part of PIP-II LINAC
- SSR2 design evolution
- SSR2 v3.1 final EM design:
  - EM parameters
  - Multipacting study
  - Transverse field asymmetry
  - HOMs up to 1 GHz
- Summary

Introduction

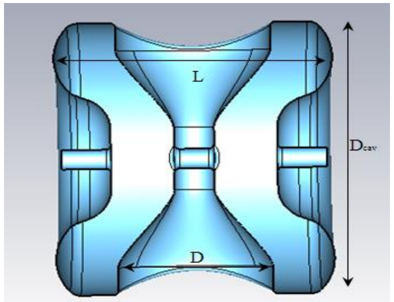


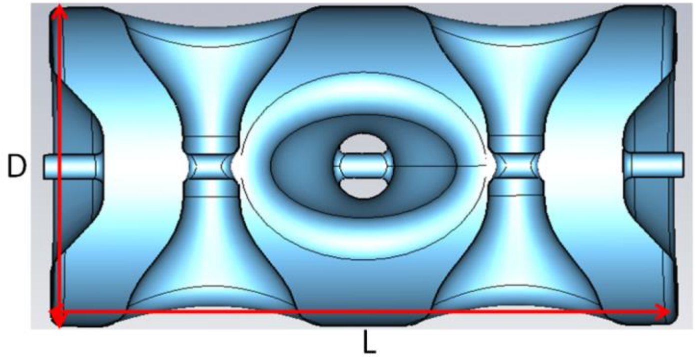
PIP-II technology map

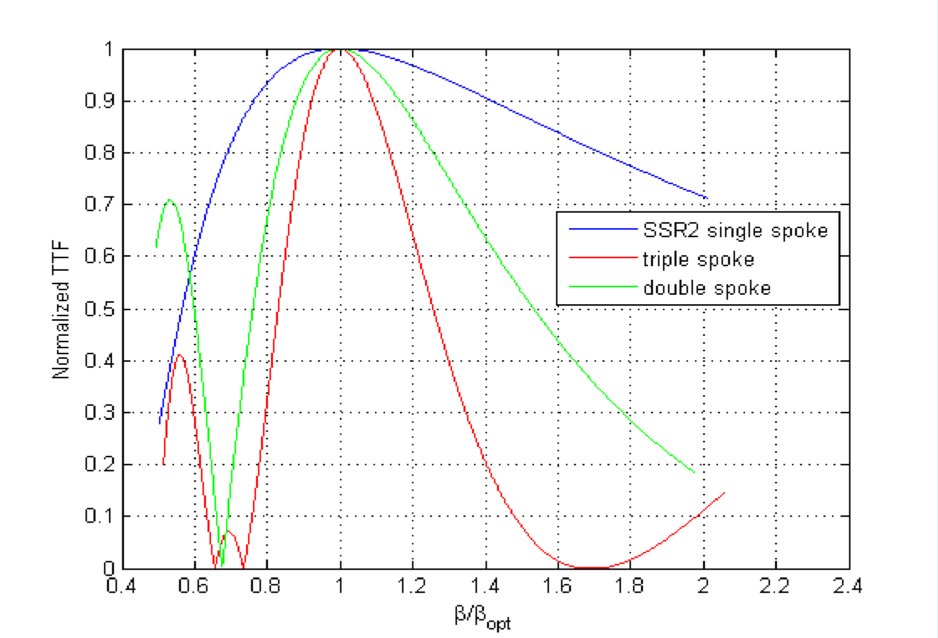
- SSR2 is the second family of Single Spoke Resonators in the SC LINAC of PIP-II.
- It will accelerate the H^- beam from the end of SSR1 to the beginning of the first 5-cell cavity section (185 MeV).
- The total number of SSR2 cavities needed is 35 divided into 7 cryomodules, having 5 resonators each.
- SSR2 beam pipe aperture is 40 mm, β_{opt}=0.47

SSR2: why single spoke?

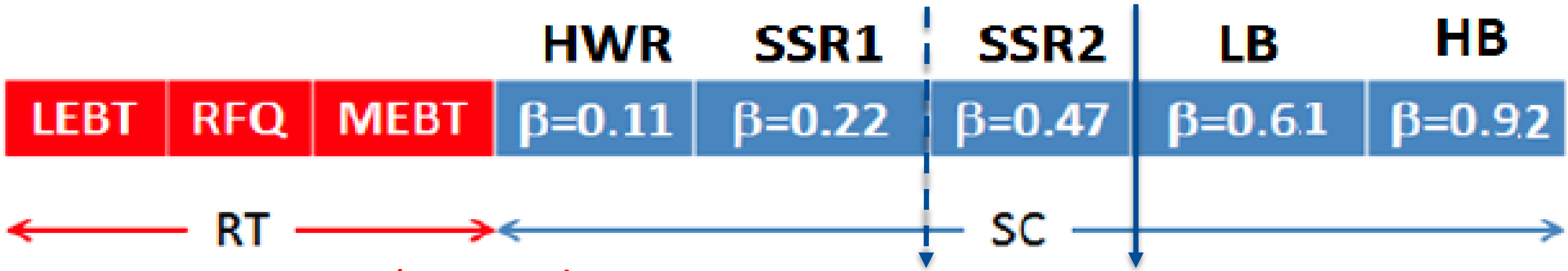
- Elliptical cavities would be too big at 325 MHz, a spoke\half wave resonator is by far more compact at low frequencies.
- Combining multiple gaps in the same structure is usually an efficient way of packing the LINAC in less space.
- **<u>Multigap structure are less effective in accelerating particles over a large beta range!</u>**







SSR2 optimal beta choice

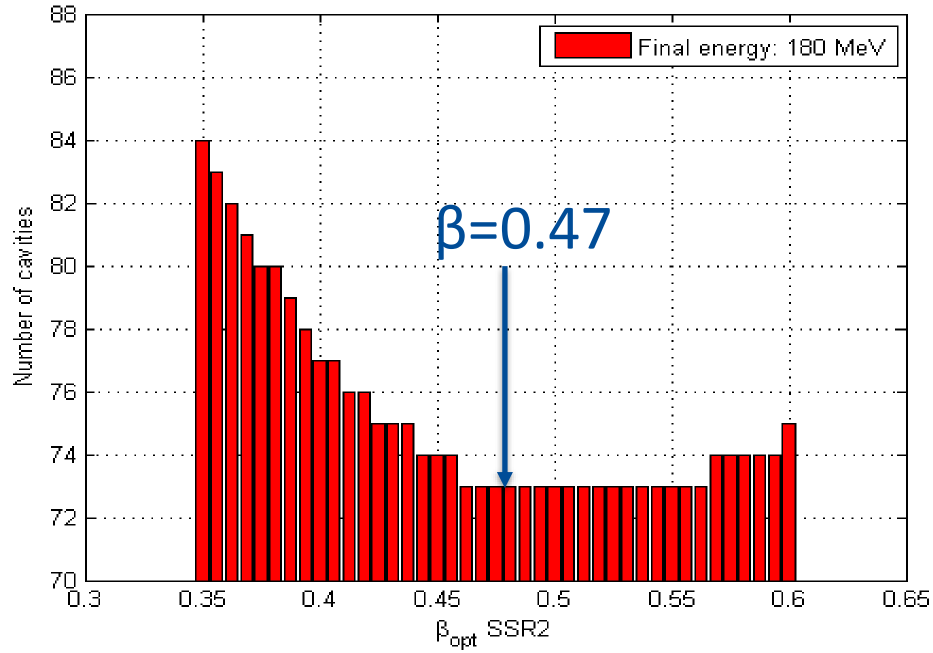


Transition energy (proton kinetic energy) and $\beta = v/c$

40 MeV $\beta=0.28$

180 MeV $\beta=0.54$

- SSR2 beta has been optimized → minimum number of cavities needed to bring the particles from 40 to 180 MeV, $\beta=0.47$.
- The normalized transit time factor needs to be scaled for each optimal beta.
- Optimal beta corresponds to peak energy gain.

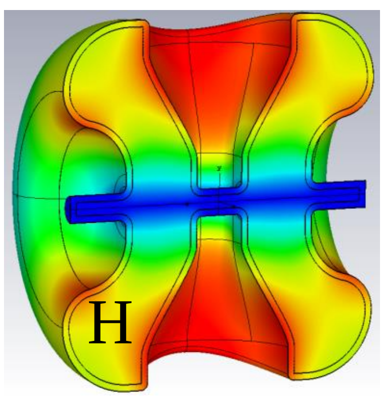


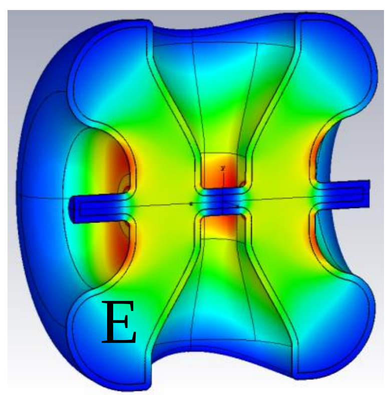
RF design and parameters

EM parameters allow 5.0 MeV energy gain at max peak fields and optimal β .

Electromagnetic design requirements	Value
Frequency, MHz	325
β optimal	0.472
Nominal energy gain at optimal beta V_{opt}, MeV	5
Maximum energy gain at optimal beta V_{max}, MeV	6
Nominal operating temperature, K	2
Operating mode	CW
Design beam average current, mA	2
Iris aperture, mm	40
Effective length $L_{eff} = 2\cdot(\beta_{opt}\lambda/2)$, mm	438
Cavity shunt impedance $(R/Q)_{opt}$ at beta optimal, Ω	305
Geometric factor, Ω	115
Surface RF electric field E_{peak}, MV/m @ 5 MeV energy gain	≤ 40
Surface RF magnetic field B_{peak}, mT @ 5 MeV energy gain	≤ 80

Requirements from **PIP-II TRS ED0009784**

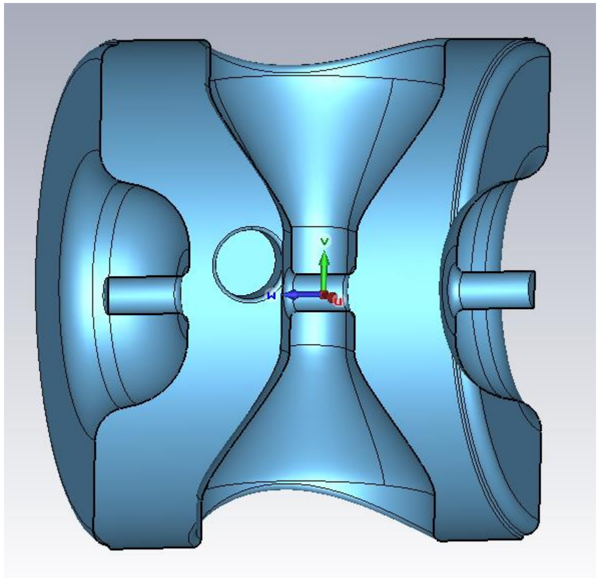




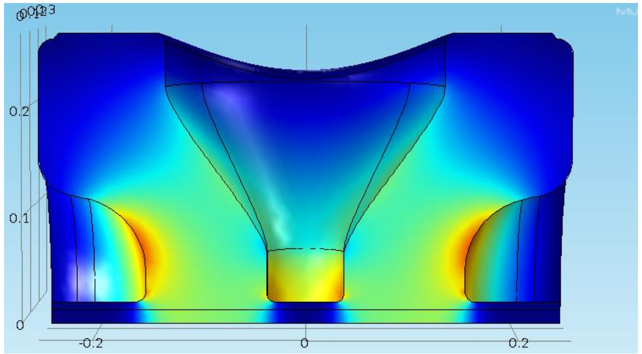
Parameters	SSR2 v 3.1 CST	SSR2 v 3.1 Comsol
Optimal beta β_{opt}	0.472	0.472
Aperture [mm]	40	40
Frequency [MHz]	325	325
Effective length $2\beta_{opt}\lambda/2$ [m]	0.436	0.436
E_{peak}/E_{acc}	3.46	3.51
B_{peak}/E_{acc} [mT/(MV/m)]	6.79	6.75
G [Ohm]	115	115
R/Q [Ohm]	305.2	305.2
E_{peak} [MV/m] @ 5 MeV	39.6	40.2
B_{peak} [mT] @ 5 MeV	77.8	77.4
Max energy gain [MeV]	5.0	5.0
Max gradient [MV/m]	11.46	11.47

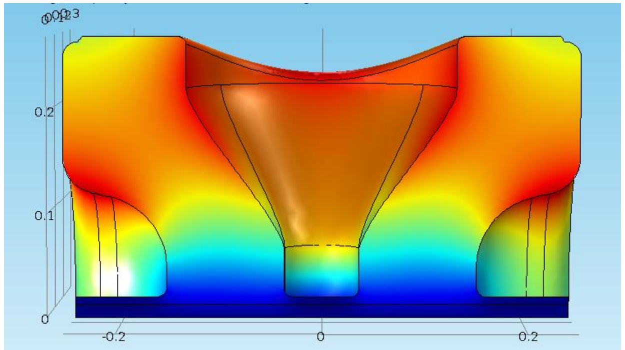
SSR2 v2.6 design evolution summary

- SSR2 has been redesigned in 2010 since beta went from 0.4 to 0.47.
- Beta optimal is now 0.47 and MP needs to be mitigated.
- Geometry has been remodeled to mitigate MP
- EM parameters satisfy PIP-II TRS
- MP study still ongoing to finalize results
- New cavity EM designed completed and shown on the right



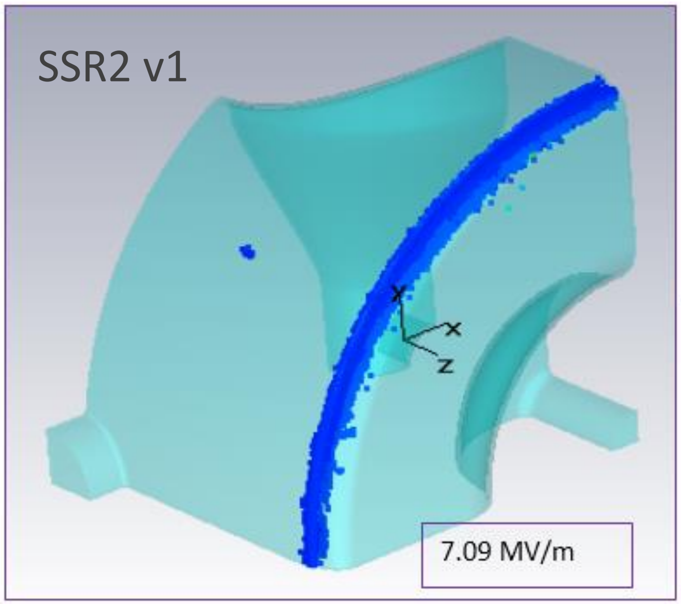
Electric (left) and magnetic (right) fields simulated with Comsol

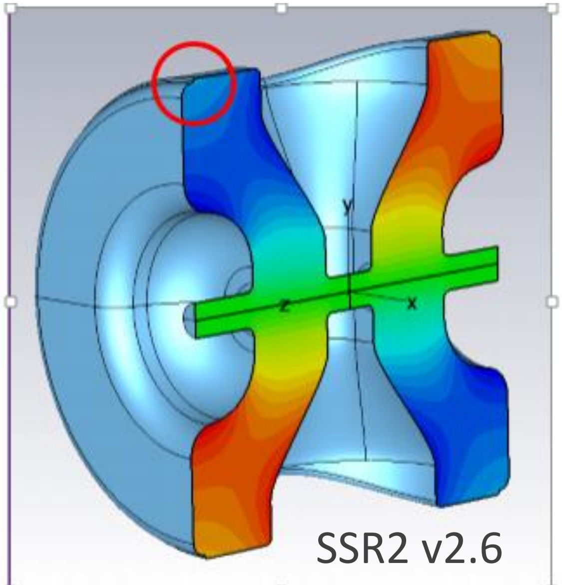


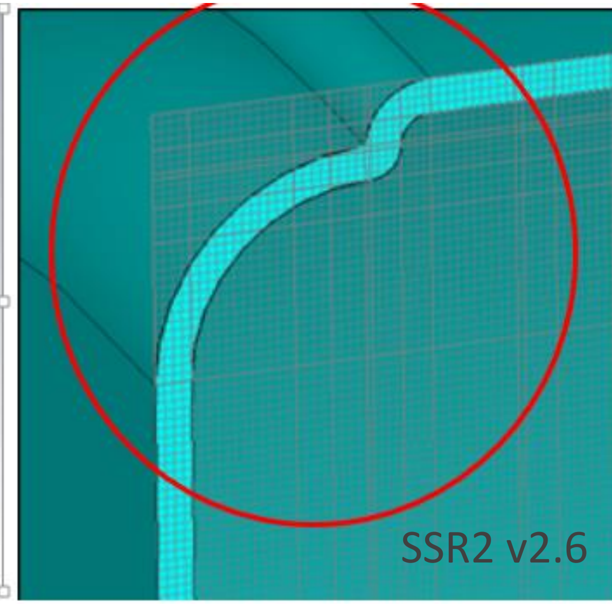


Multipacting mitigation

Most severe multipacting take place near transition of cylindrical part to end walls. Several design options of this transition were considered. Most significant improvement was achieved after introducing additional step in the transition are.

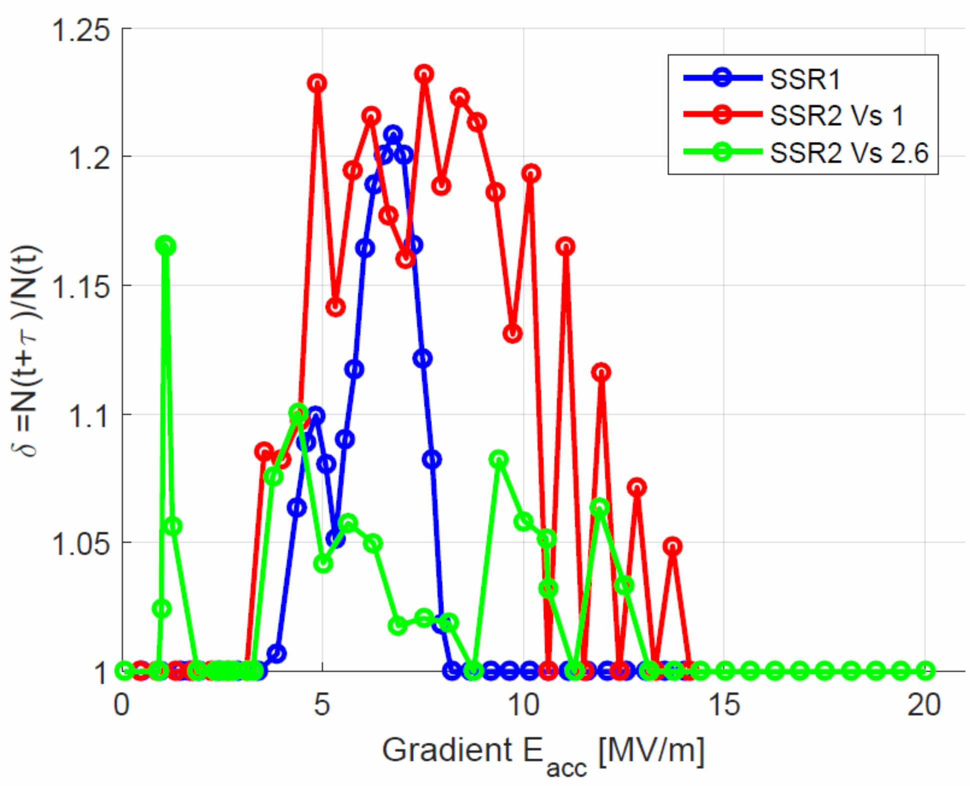






Modification of this transition reduce multipacting in operating range of cavity fields.

SSR2 – Multipacting comparison

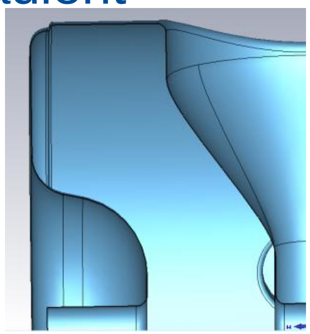


Parameters	SSR2 v1	SSR2 v2.6
Optimal beta	0.471	0.475
Epeak/Eacc	3.45	3.38
Bpeak/Eacc [mT/(MV/m)]	6.107	5.93
G [Ohm]	112.98	115.2
R/Q [Ohm]	289.94	296.6

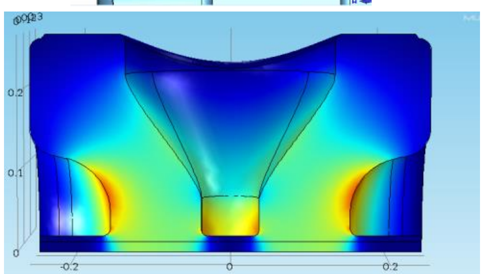
The secondary electron multiplication, $\delta = N(t+\tau)/N(t)$, significantly reduced in the operating gradient range of 5-12 MV/m. Comparison with SSR1 cavity demonstrates that multipacting in the modified SSR2 cavity version 2.6 can be processed way easier than in SSR1 cavity.

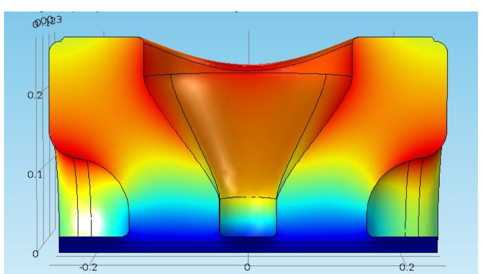
SSR2 from v2.6 to v3.1

- Most severe multipacting take place near transition of cylindrical part to end walls.
- Eliminating the corner seems to improve the MP barrier at operating gradient

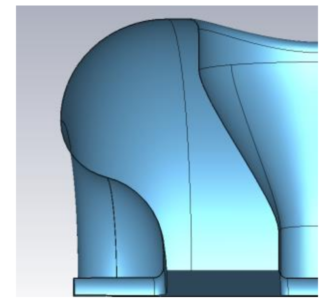


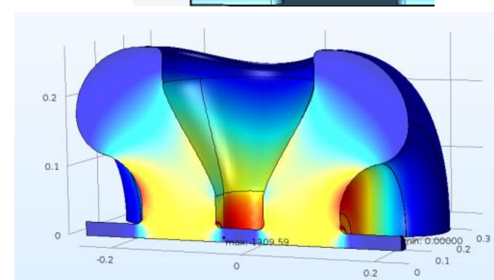
v2.6

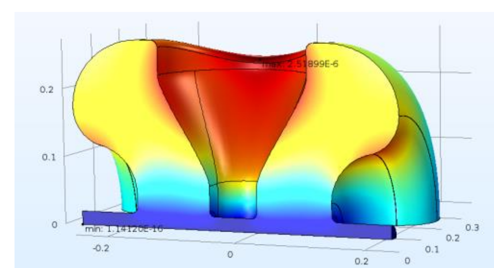




v3.1

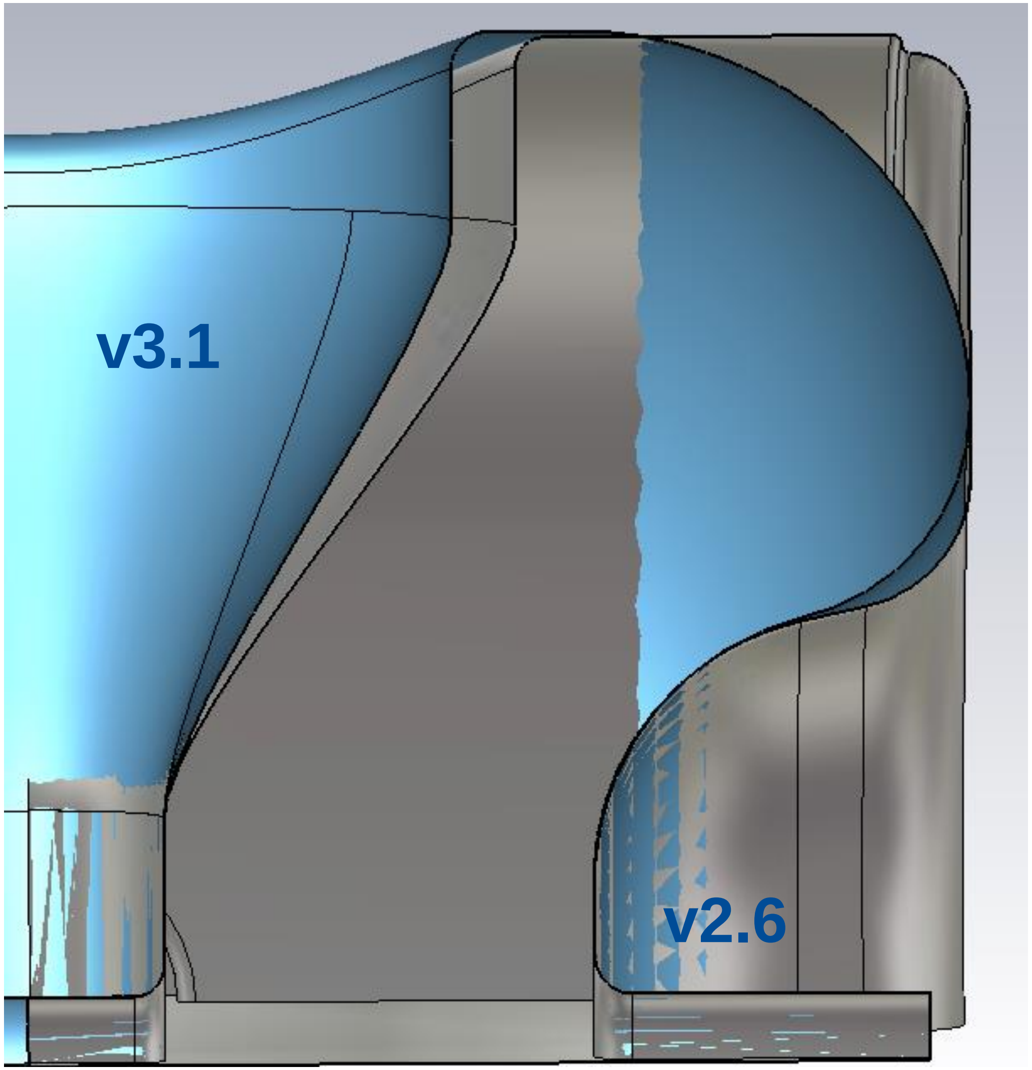




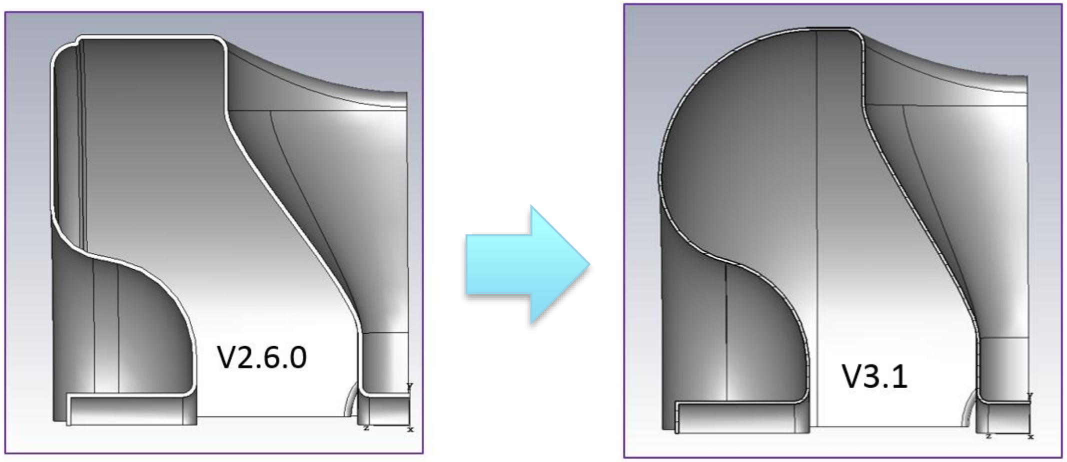


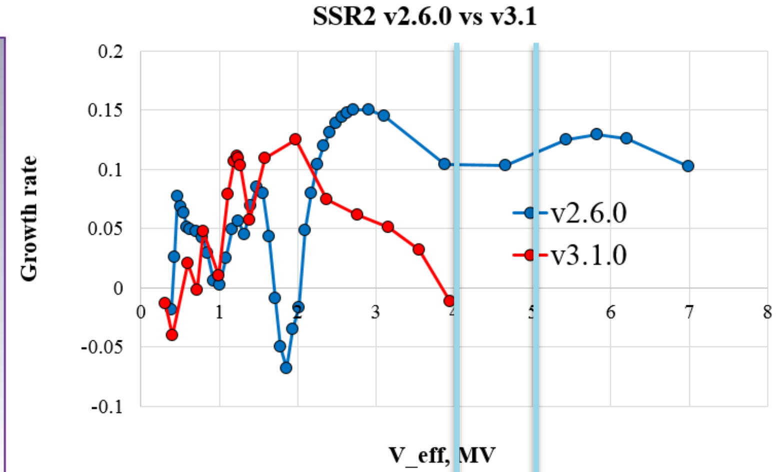
SSR2 from v2.6 to v3.1 Geometry comparison

- Overlapping the two geometries for comparison→ v2.6 in gray v3.1 in blue.
- Cavity Z length has not been changed.
- Cavity radius has changed minimally.
- New shape improves MP but it penalizes magnetic field volume (see following slides)

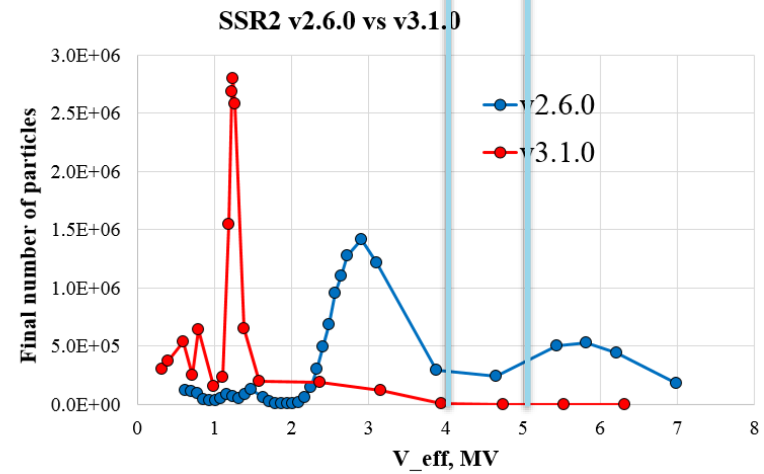


Design evolution steps led by MP reduction

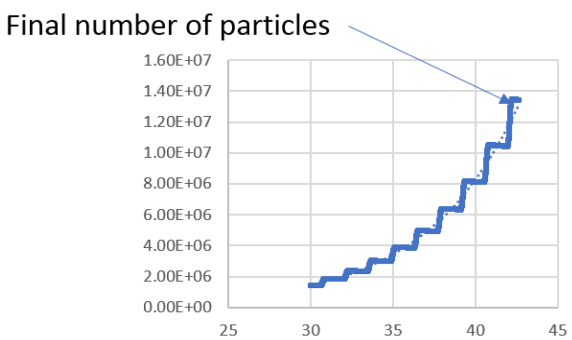




Operating Voltage range



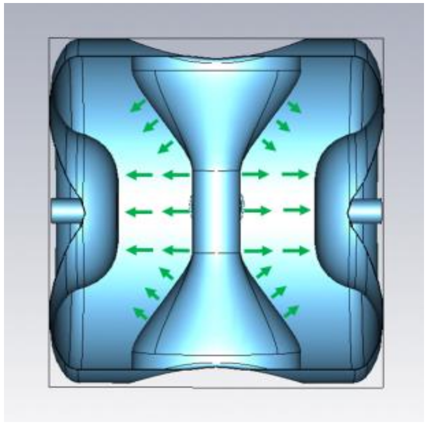
- All cases have been simulated for the same amount of time, final number of particles is comparable from case to case

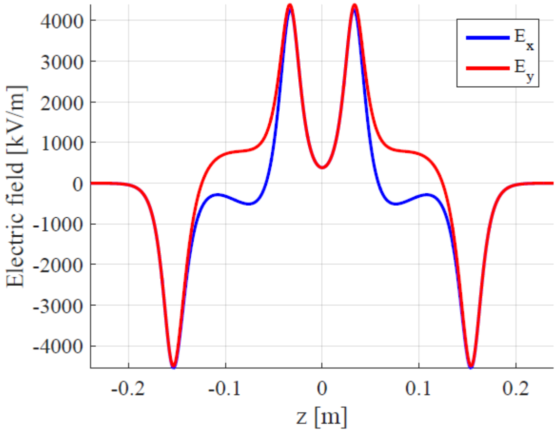


Transverse fields asymmetry I

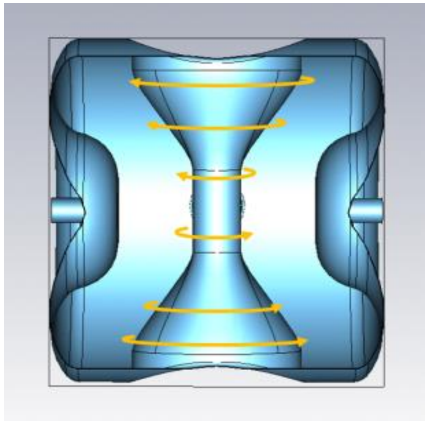
Spoke resonators have a central electrode that lies on one of the axes perpendicular to the particles motion, breaking axial symmetry of the cavity.

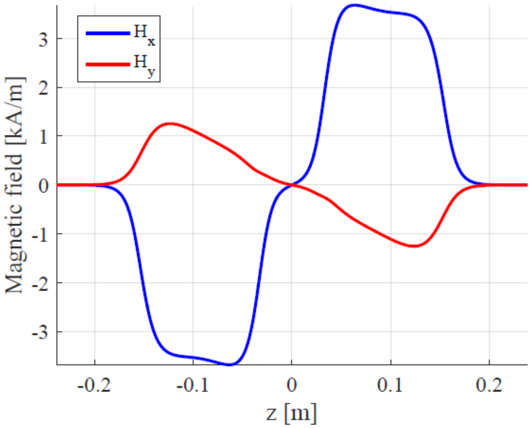
Electric field SSR2 fundamental mode sketch.





Magnetic field SSR2 fundamental mode sketch.

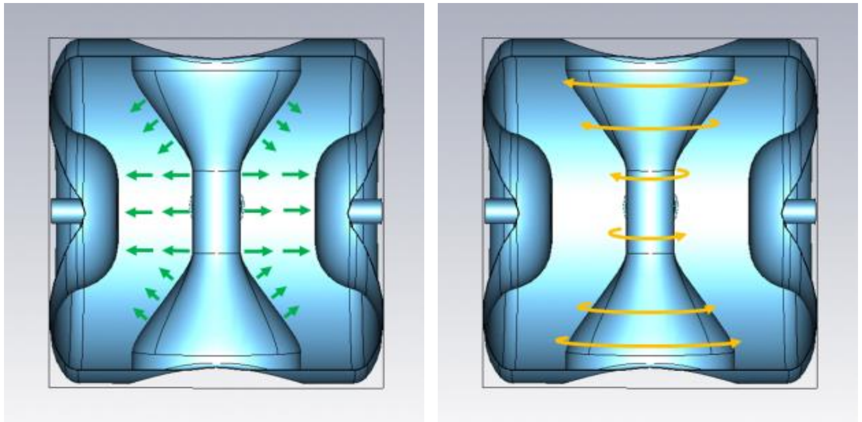




Transverse fields asymmetry II

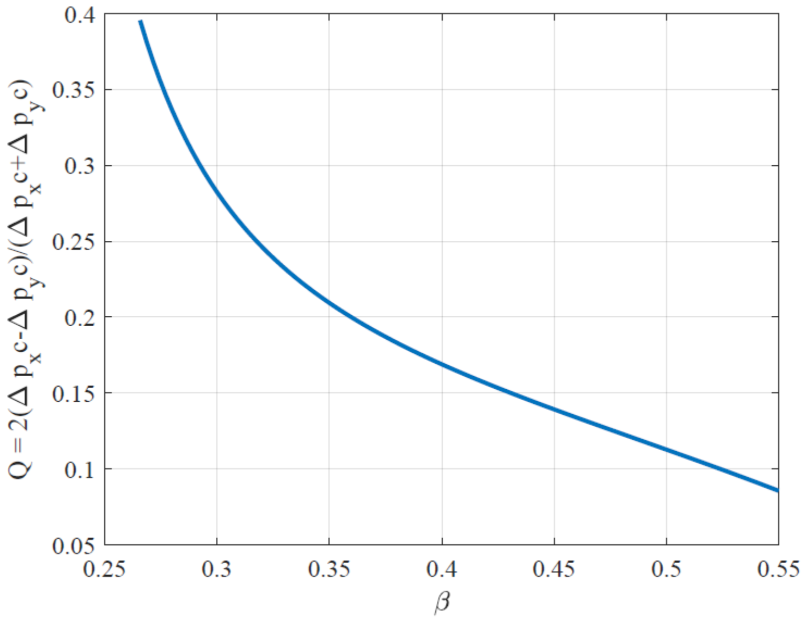
Spoke resonators have a central electrode that lies on one of the axes perpendicular to the particles motion, breaking axial symmetry of the cavity.

Electric and magnetic field SSR2 fundamental mode sketch.



$$Q = \frac{\Delta p_x(r,0)c - \Delta p_y(r,\pi/2)c}{\left(\Delta p_x(r,0)c + \Delta p_y(r,\pi/2)c\,\right)/2}\,.$$

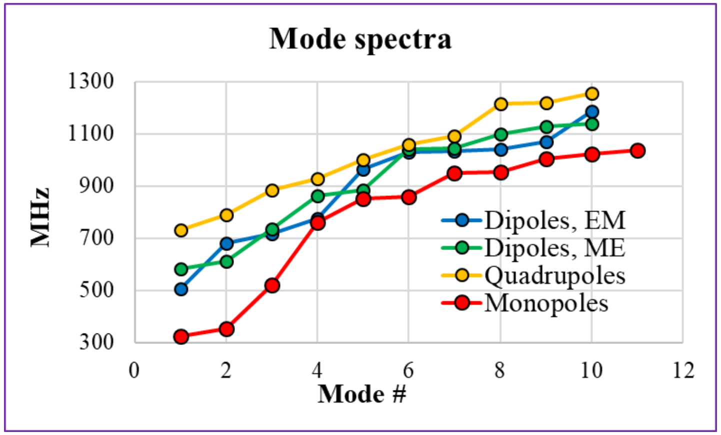
Q vs particle beta for the whole energy range of SSR2 v3.1 (35-185 MeV)

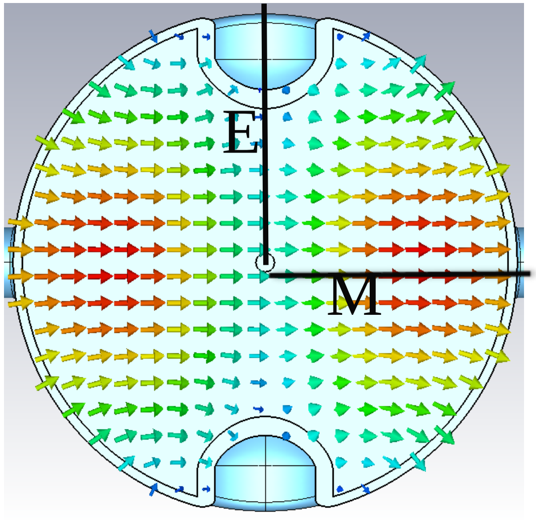


The quadrupole field asymmetry of SSR2 has been studied and it is within the range of the quadrupole corrector integrated in the solenoids.

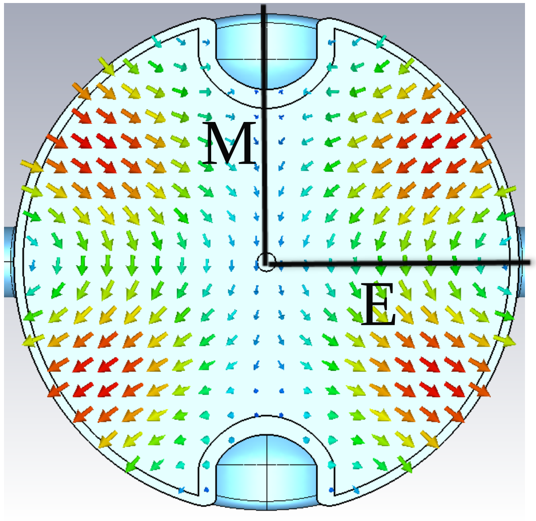
Monopole and HOM spectra

Mode #	Dipole, EM	Dipole, ME	Quadrupole	Monopole
1	505.3131	584.1004	732.6224	325
2	679.6355	612.0279	790.6674	354.2731
3	716.9426	733.3314	885.0019	520.146
4	774.1299	863.4636	929.4667	760.1349
5	962.6583	885.7857	1000.21	852.1499
6	1030.171	1042	1056.822	859.9572
7	1032.94	1045.354	1089.756	948.0935
8	1038.535	1098.179	1214.19	954.8068
9	1070.175	1127.068	1218.528	1004.807
10	1185.566	1137.474	1253.502	1022.708
11				1035.464

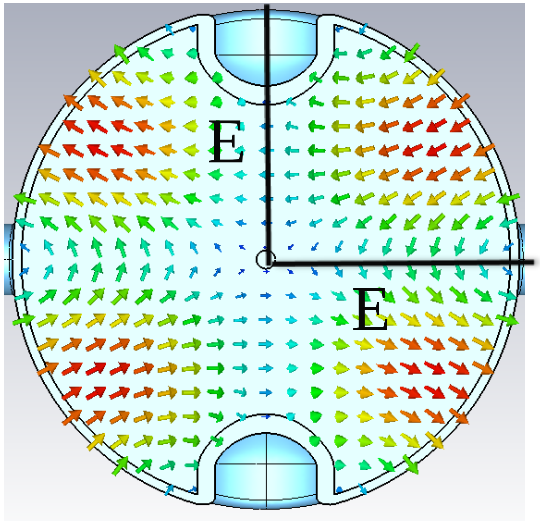




Dipole EM



Dipole ME



Quadrupole

Summary

- SSR2 v 3.1 improves MP characteristic: no MP in operating voltage range (4-5 MV) and up to 6 MV.
- EM parameters satisfy PIP-II project TRS providing reliably 5 MeV accelerating voltage.
- Transverse field asymmetry and HOMs studies have been finalized.
- No outstanding issues from the electro magnetic point of view.

Back-up

Higher surface magnetic field: not critical!

- SSR2 v3.1 magnetic peak field @ 5 MeV gain will exceed 77 mT from both Comsol and CST.
- Given the experience of SSR1 test this does not represent a critical value: all cavities quench above 100 mT.