Project X
Collaboration Meeting

from Friday 11 September 2009 (08:00)
to Saturday 12 September 2009 (18:00)
US/Central
at One West
support: sasse@fnal.gov

Linac Design: Single-Spoke Cavities.

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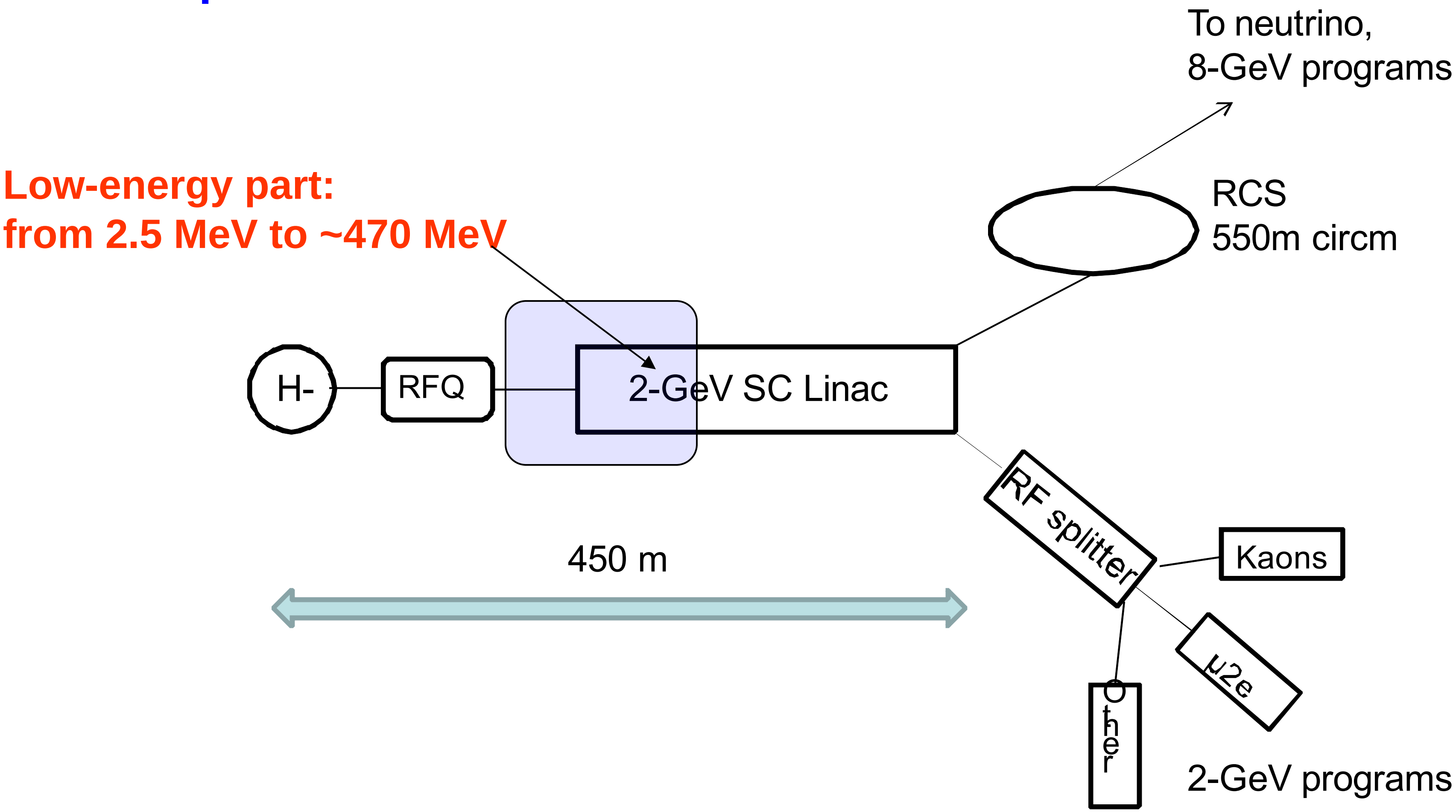
(on behalf of the Fermilab TD team:
N. Solyak, I. Gonin, A. Lunin,
N. Perunov, and T. Habibouline)

The schematic layout of ICD-2 accelerator complex

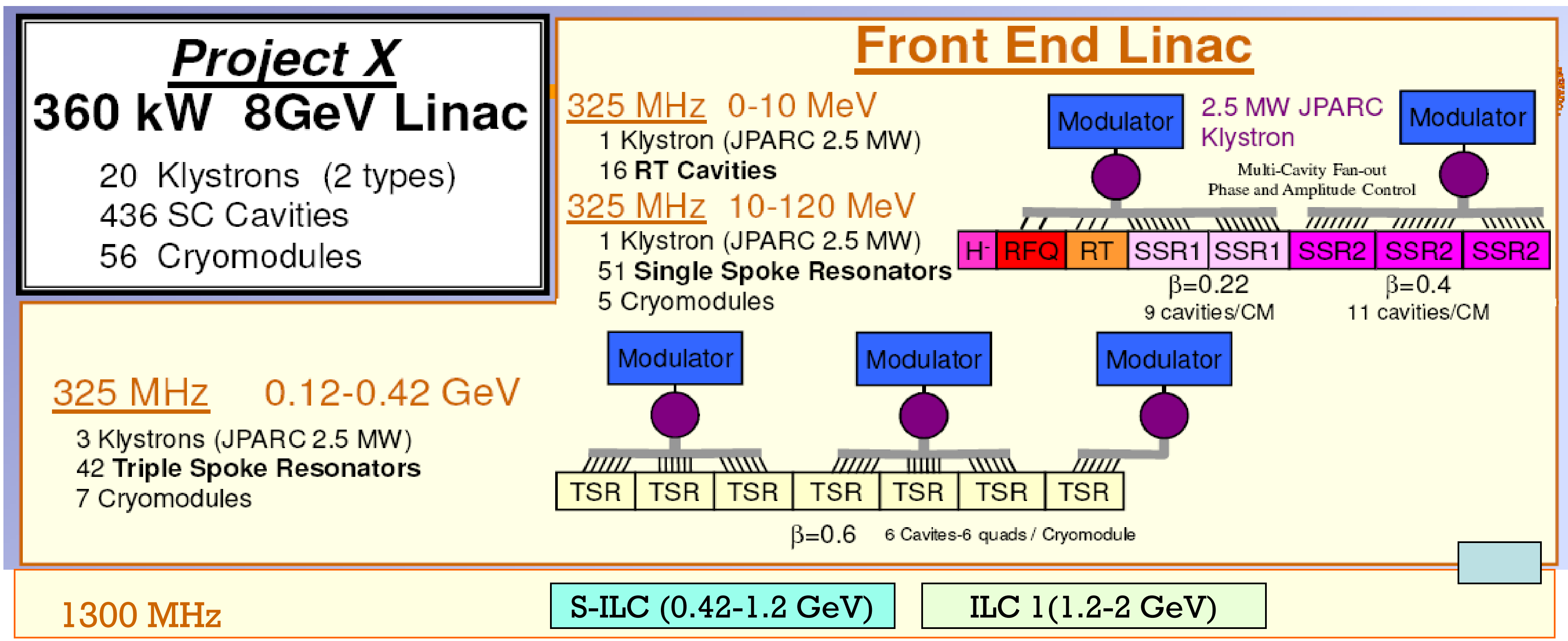


CW Linac:

- Energy: 2 GeV;
- Current: 1 mA average, 10 mA pulsed (100 ns trains, period 1000 ns)
- Beam dynamics close to HINS!

Suggestion:

- same structure at 325 MHz and about the same break points as in HINS:
- **Changes: CW RFQ and replace RT cavities with SC (1 family)**
- 1.3 GHz linac is the same (S-ILC and ILC-1) with E_{acc} ~18 MV/m



Break points in current design of HINS

E, MeV	β	Type	
0.05-2.5	0.073	RFQ, P_{wall} = 350 kW (pulsed)	→RT
2.5-10	0.073-0.146	RT (9 families), P_{wall}=360 kW (pulsed)	→SC
10-32	0.146-0.261	SSR1 (β=0.22)	OK
32-117	0.261-0.5	SSR2 (β=0.4)	OK
117-400	0.5-0.713	TSR (β=0.6)	OK

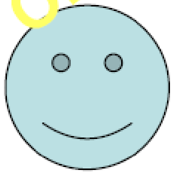
- For CW operation SC cavities are desired.
- No SC RFQ in operation for protons (80 MHz SRFQ for heavy ions operates for PIAVE linac)
  → Choice: RT RFQ;
- RT CW Quarter-Wave or
  → Half-Wave SC cavities for the energy from 2.5 MeV to 10 MeV.

Acceleration from 2.5 MeV to 10 MeV (1)

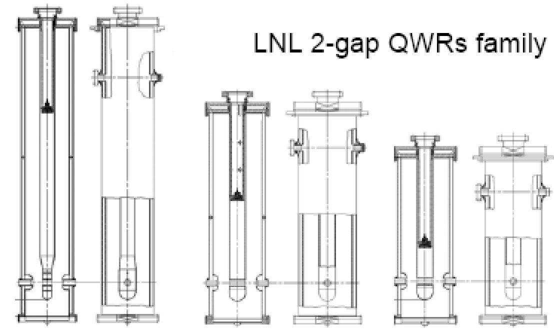
Quarter-Wave resonators

OPERATING

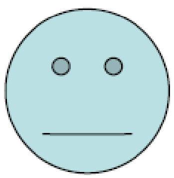
48≤f≤160 MHz, 0.001≤ β_0≤0.2



- Compact
- Modular
- **High performance**
- **Low cost**
- **Easy access**
- Down to very low beta

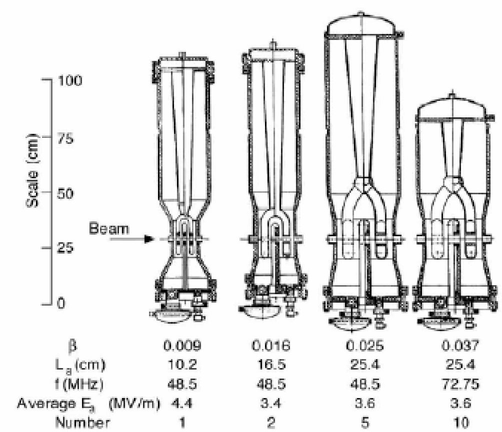


LNL 2-gap QWRs family



- Dipole steering above ~100 MHz
- Mechanical stability below ~100 MHz
- (Quadrupole steering)

Very successful



ANL 4-gap QWR family

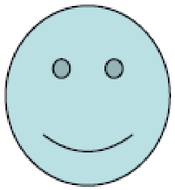
Potential problem:

- **Field asymmetry needs to be compensated : beam offset, dipole steering or shaping the gap**
- **Mechanical stability**

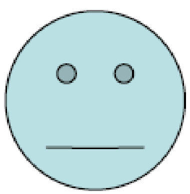
Half-Wave resonators

TESTED

$160 \leq f \leq 352$ MHz, $0.09 \leq \beta_0 \leq 0.3$

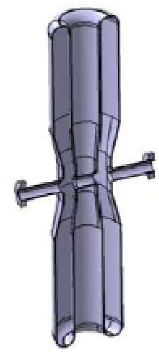


- **No dipole steering**
- High performance
- Lower E_p than QWRs
- Wide beta range
- Very compact

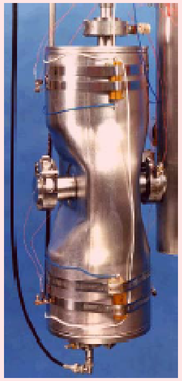


- Not easy access
- Difficult to tune
- **Less efficient than QWRs**
- (Quadrupole steering)

best use around 200 MHz



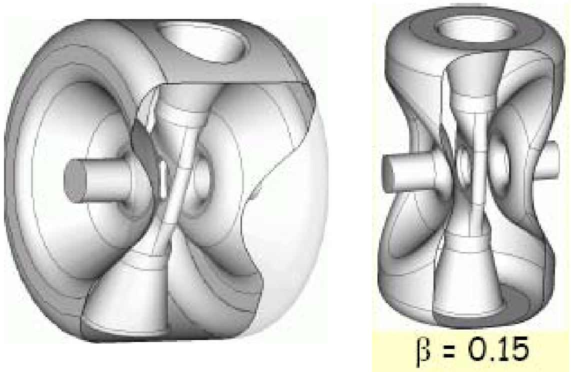
MSU 322 MHz β=0.28



The first 355 MHz SC HWR ANL - β=0.12

ACCEL 176 MHz SC HWR β=0.09

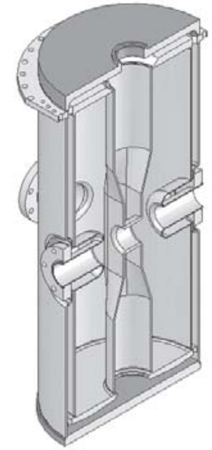
Spoke or Half-Wave Resonator ?



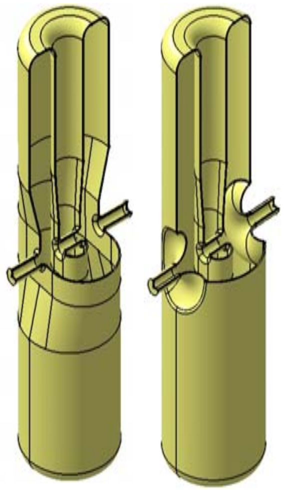
Spoke and HWR performances are comparable

352 MHz Resonator type	HWR	Low-β Spoke [10]	Spoke [11]
β optimum	0.17	0.21	0.18
Aperture (mm)	30	50	50
L_{re} (mm)	232	286	385
L_{ac} (mm)	180	99	85
L_{ac} definition	L_{max}	L_{in}	$\beta\lambda$
U/E_a^2[mJ/(MV/m)^2]	67	39	21
$\Gamma = R_s \times Q$ (Ω)	55	64	72
V_{acc} (MV) (1)	0.93	0.83	0.69
P_{rf} (W) (1)	6.9	9.2	4.1
E_p (MV/m) (1)	30	21	29

normalized to: *Bpk* = 62 mT and *Rs* = 96.4 nΩ.

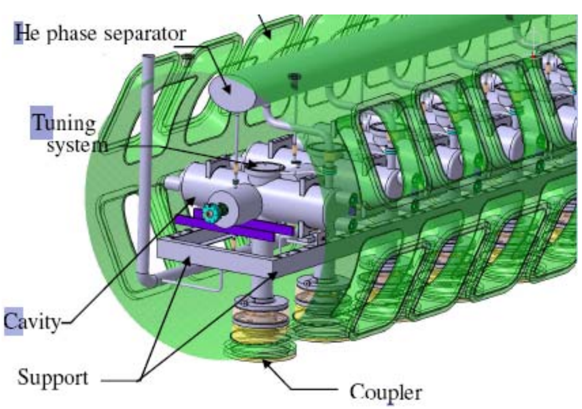


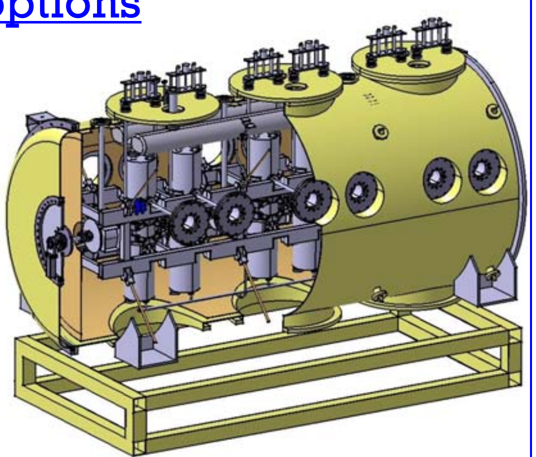
352 MHz β=0.17, SC HWR (A. Facco, INFN)



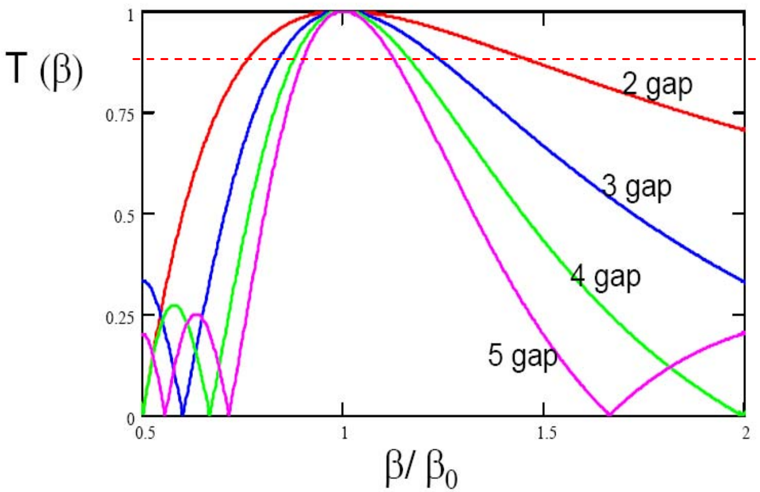
HWR: "Juelich-type" (left) and "ANL-type" (right) 176 MHz, β=0.14

Possible CM design options

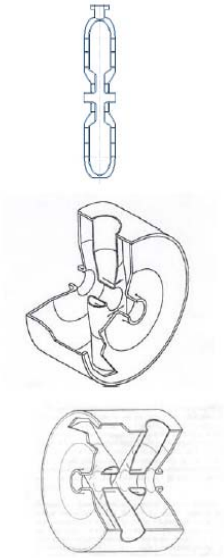




Transit time factor curves (normalized)

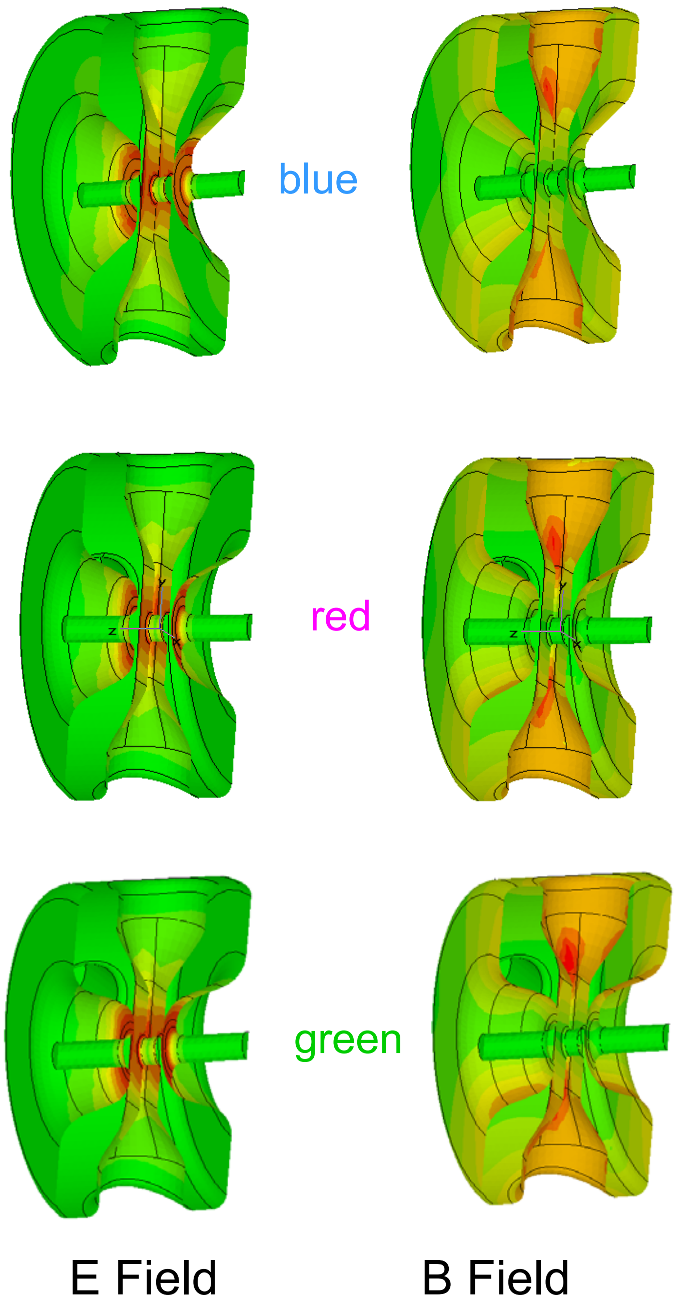


Normalized transit time factor curves vs. normalized velocity, for cavities with different number of gap



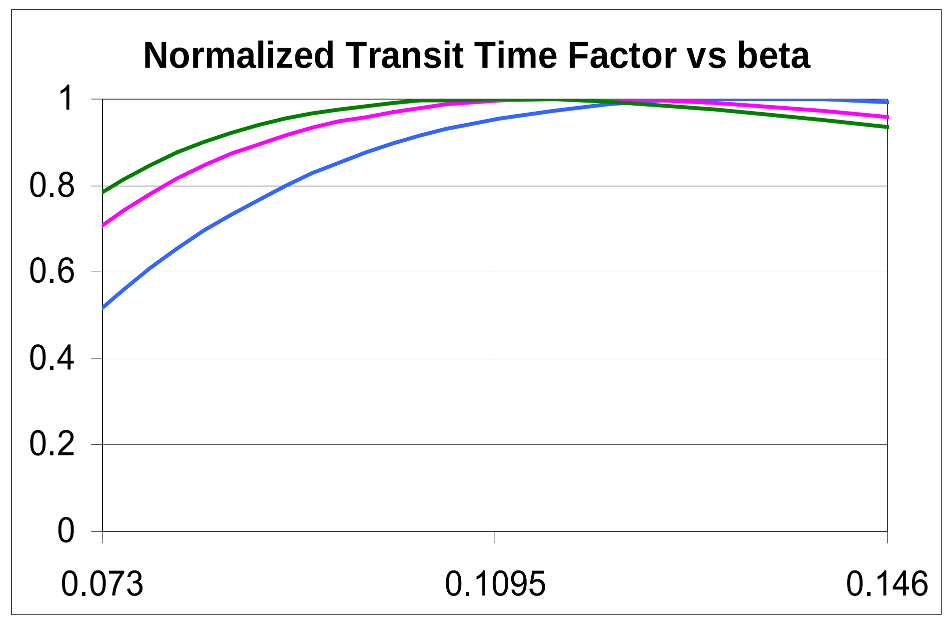
One family of the QW cavities:

- QWR (β=0.097): 0.073< β<0.146 or 2.5MeV< E < 10 MeV;
- T > 0.85! Gradient ~ 6 MeV/m, or > 460 keV/cavity ($\Delta E = G\beta\lambda\langle T \rangle$).
- Number of cavities = 16 (the same 16 RT in HINS)
- Gain > 0.46MeV per cavity, Total Gain = 7.5 MeV



F(MHz)	325	325	325	325
$\beta_{optimal}$	0.135	**0.117**	0.11	0.22
R_{cavity},mm	210	**191.5**	180	245.6
R/Q, Ω	150	**130**	120	240
TTF, Average	0.891	**0.944**	0.953	0.952
$E_{max}/E_{acc}/E_{max}/E_{acc*}$	5.4/6.1	**6.8/7.1**	7.0/7.3	3.9/4.1
$H_{max}/E_{acc}/H_{max}/E_{acc*}$ **(mT/MV/m)**	10.9/12.3	**10.3/11**	10.8/11.3	5.8/6.1
D_{eff}=(2*βλ/2),mm	124.6	**108**	101.5	203

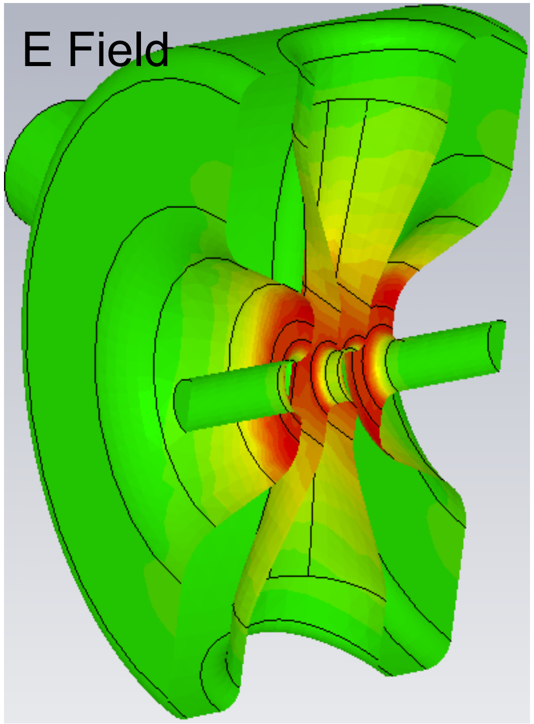
$$E_{acc*}=E_{acc}(\beta_{optimal})^{*}\ \text{TTF, Average}$$

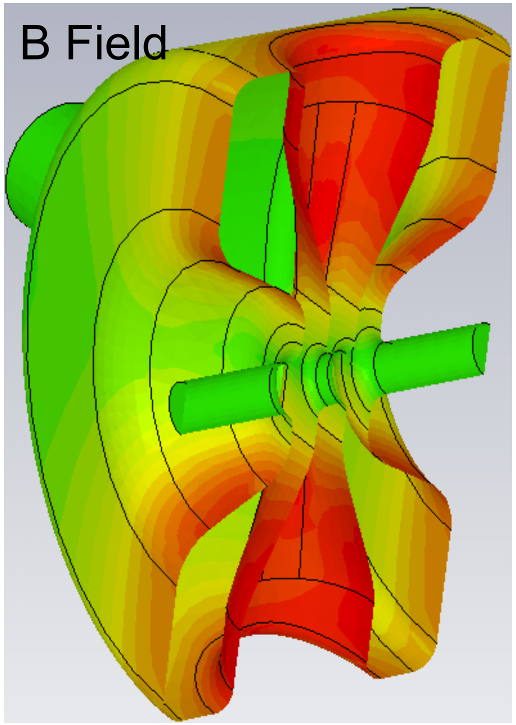


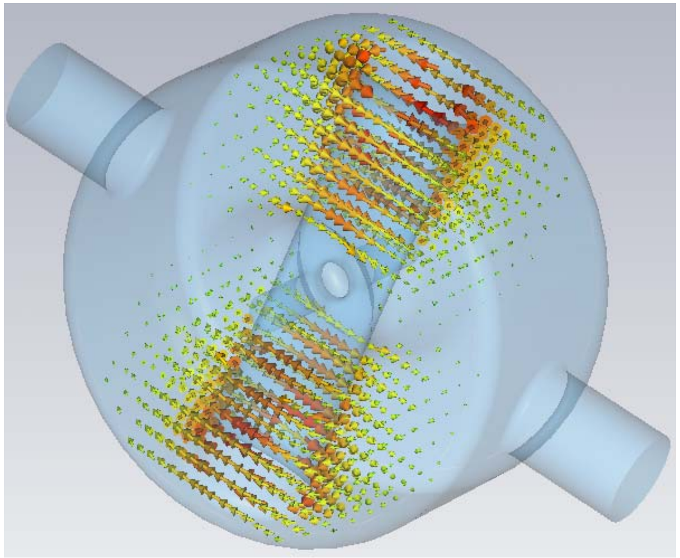
OPTIMIZATION OF SSR β=0.117

F(MHz)	325
$\beta_{optimal}$	0.117
R_{cavity},mm	191.7
R/Q, Ω	120
TTF, Average	0.94
E_{max}/E_{acc}/E_{max}/E_{acc*}	6.15/6.55
H_{max}/E_{acc}/H_{max}/E_{acc*} **(mT/MV/m)**	6.9/7.3
$D_{eff}(2^*\beta\lambda/2)$,mm	108

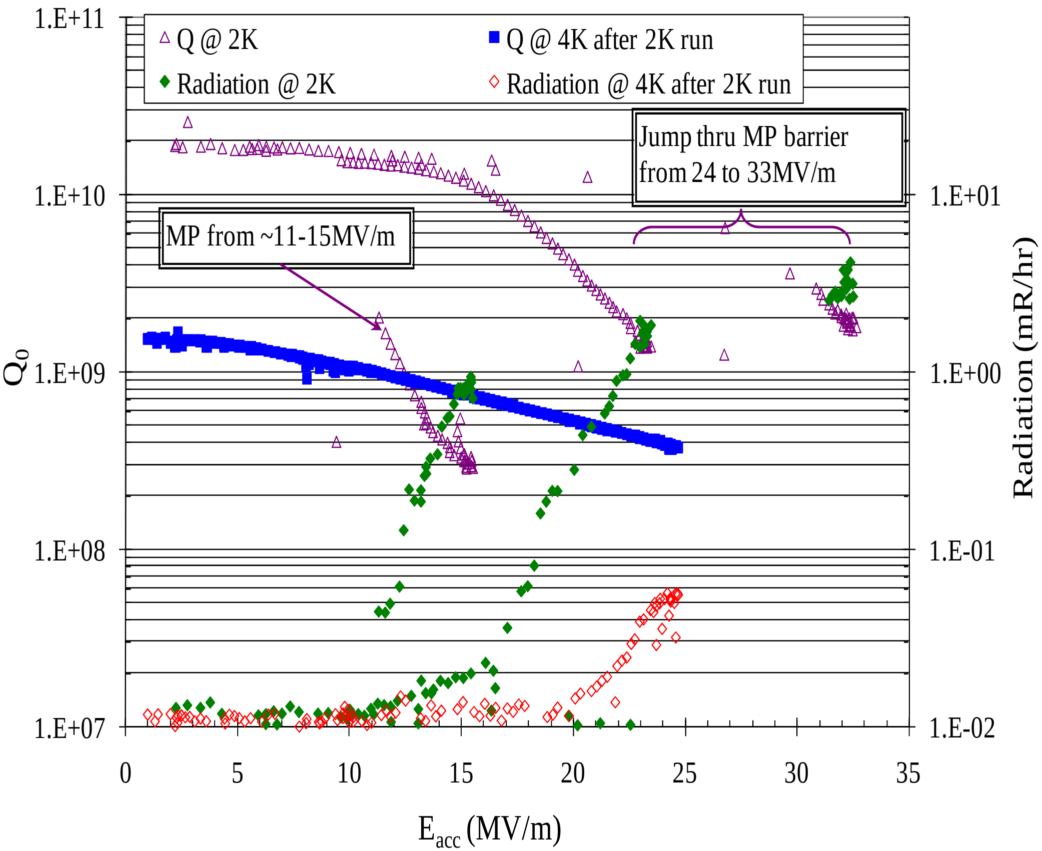
$E_{acc*}=E_{acc}(\beta_{optimal})^*$ TTF, Average

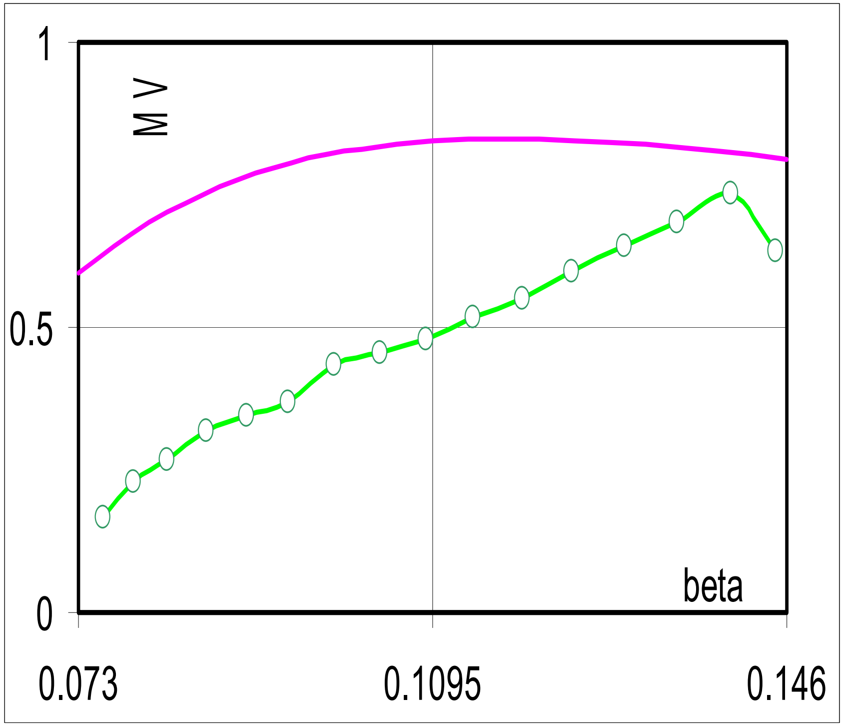






OPTIMIZATION OF SSR β=0.117 (cont.)





Gain/Cavity vs beta

Pink : H_{max} = 59mT

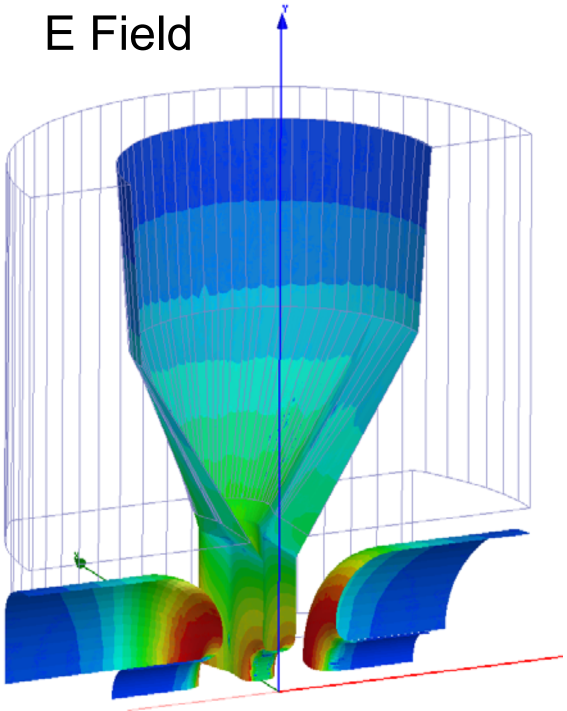
Green: RT

Q_0 vs. E_{acc} from the first cold test of SSR1-02.
Maximal E_{acc}= 25 MeV/m @4K; 33MeV/m@2K
At CW assume E_{acc}= **15** MeV/m
that corresponds to:
E_{max}= 40 MV/m and
H_{max}= 59 mT

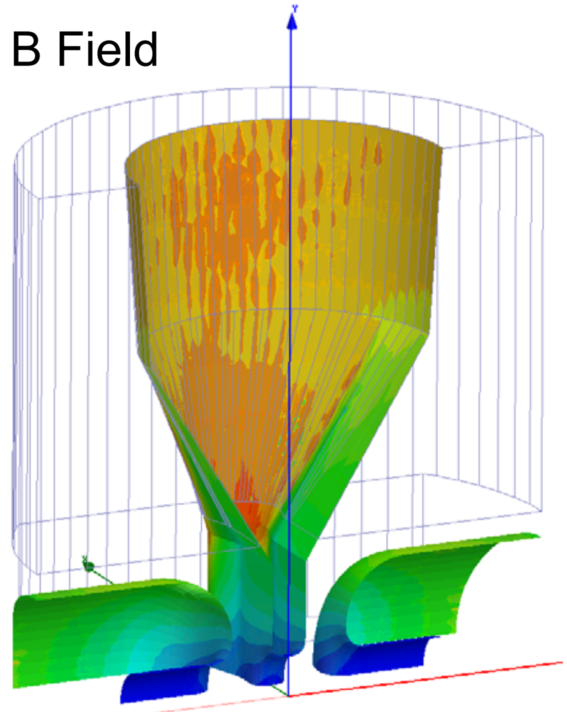
- Based on experimental data it is possible to reduce number of cavities, if no limitation on beam dynamics

OPTIMIZATION OF HWR β=0.1

E Field

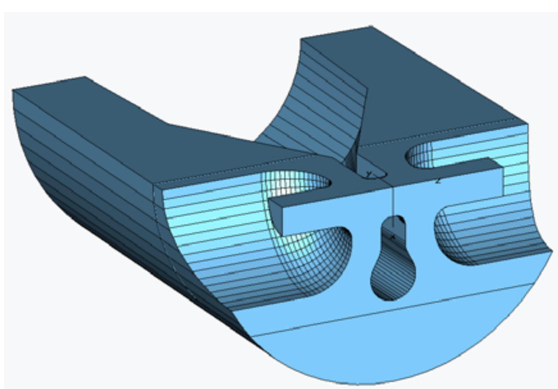


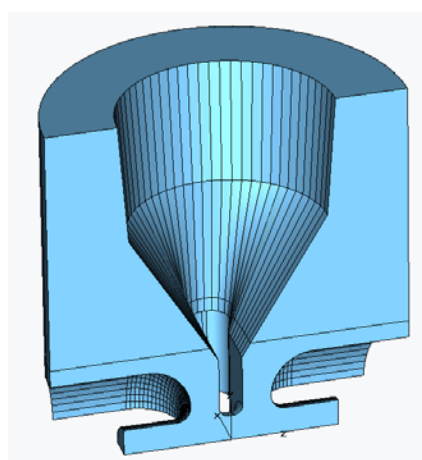
B Field

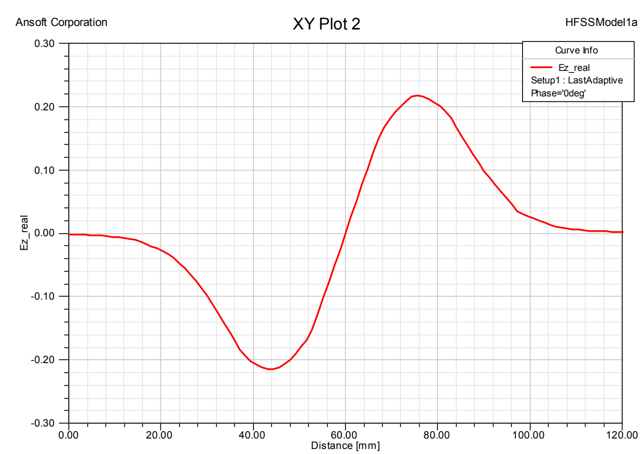


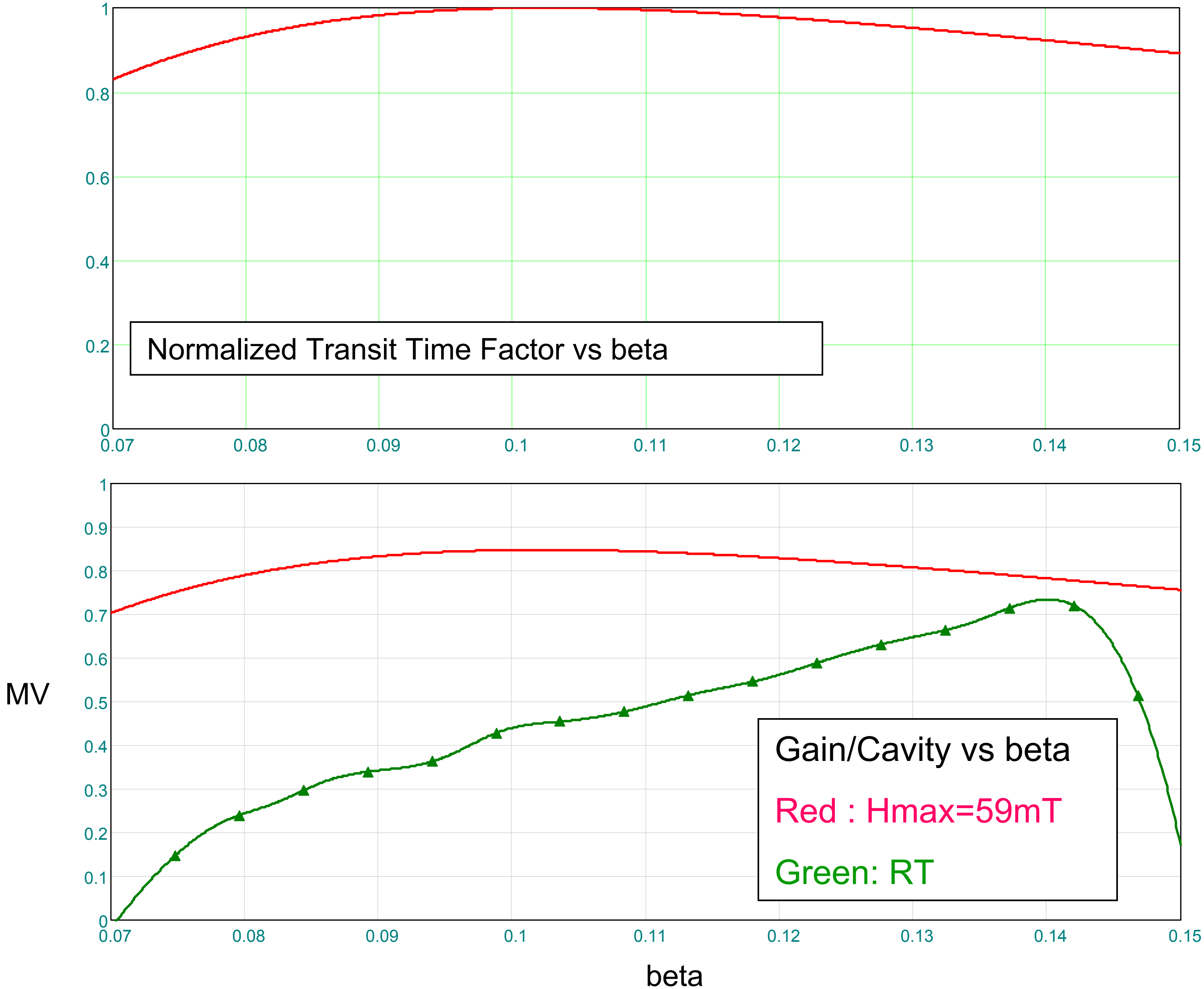
F(MHz)	225
$\beta_{optimal}$	0.1
D_{cavity},mm	200
R/Q, Ω	80
TTF, Average	0.96
E_{max}/E_{acc}/E_{max}/E_{acc*}	6.2/6.5
H_{max}/E_{acc}/H_{max}/E_{acc*} **(mT/MV/m)**	6.5/6.8
$D_{eff}(2*\beta\lambda/2)$,mm	94

$E_{acc*}=E_{acc}(\beta_{optimal})*$ TTF, Average



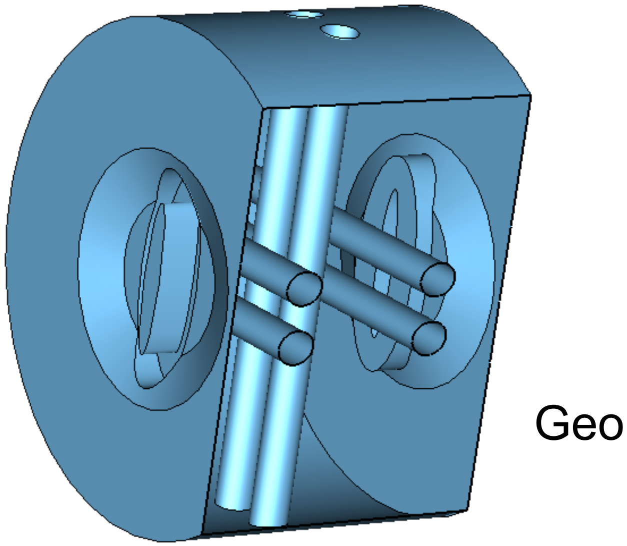


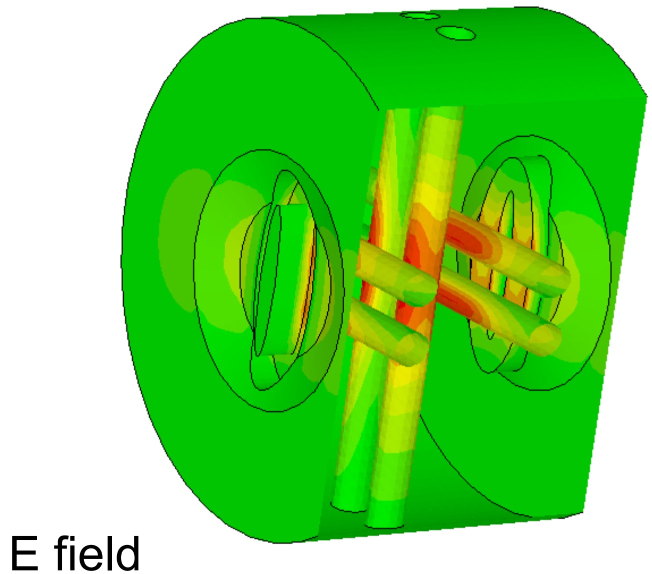


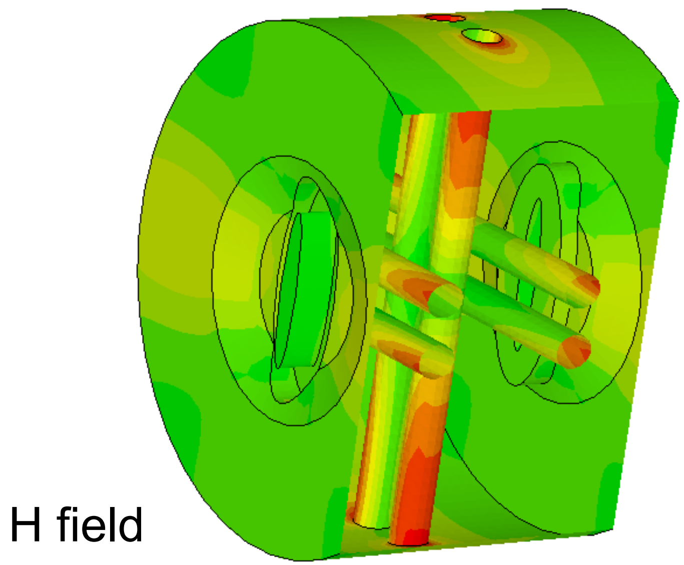


Normalized Transit Time Factor vs beta
Gain/Cavity vs beta
Red : Hmax=59mT
Green: RT
MV
beta
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15

Slot Cylindrical Cavity, β=0.11

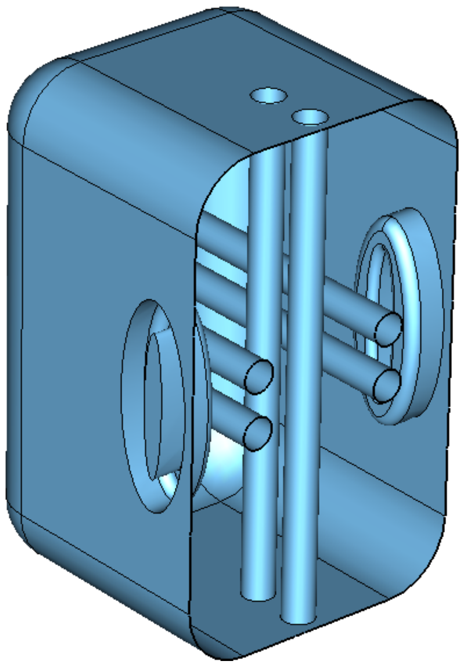




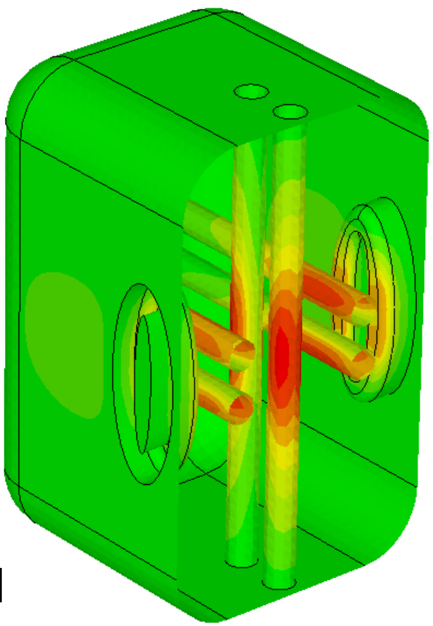


F(MHz)	362.3
R/Q	446
E_{max}/E_{acc}	7.32
H_{max}/E_{acc}	11.4 (mT/MV/m)
$D_{eff}=(4*\beta\lambda/2)$	187.5mm

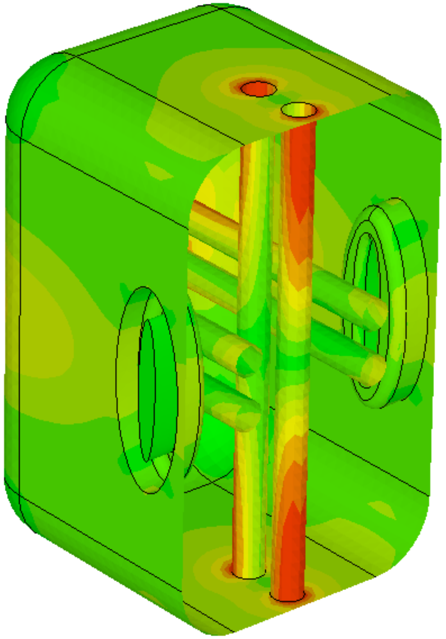
Slot Rectangular Cavity, beta=0.11



Geo



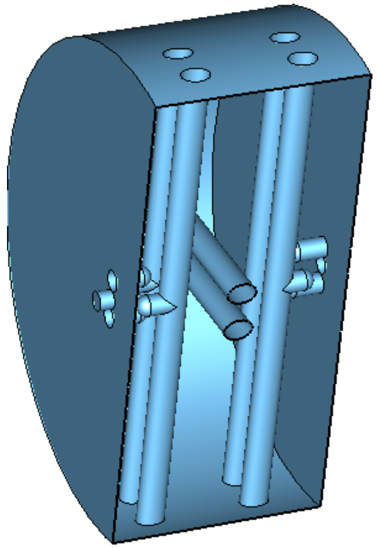
E field



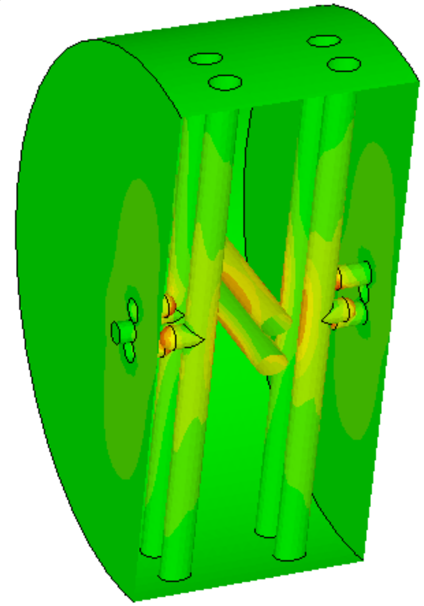
H field

F(MHz)	343.2
R/Q	455
E_{max}/E_{acc}	5.28
H_{max}/E_{acc}	11.1 (mT/MV/m)
D_{eff}=(4*βλ/2)	187.5mm

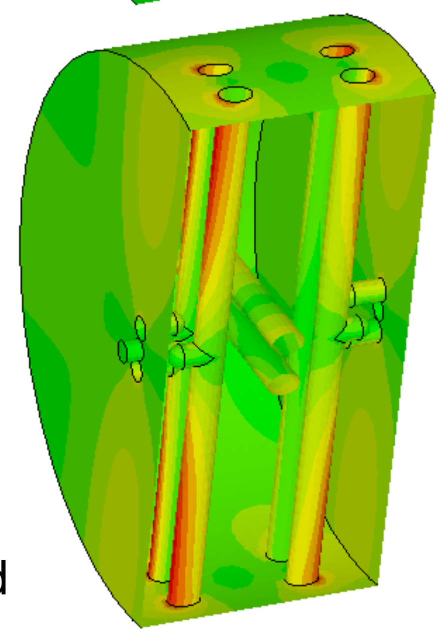
Slot Finger Low beta Cavity, beta=0.08



Geo



E field

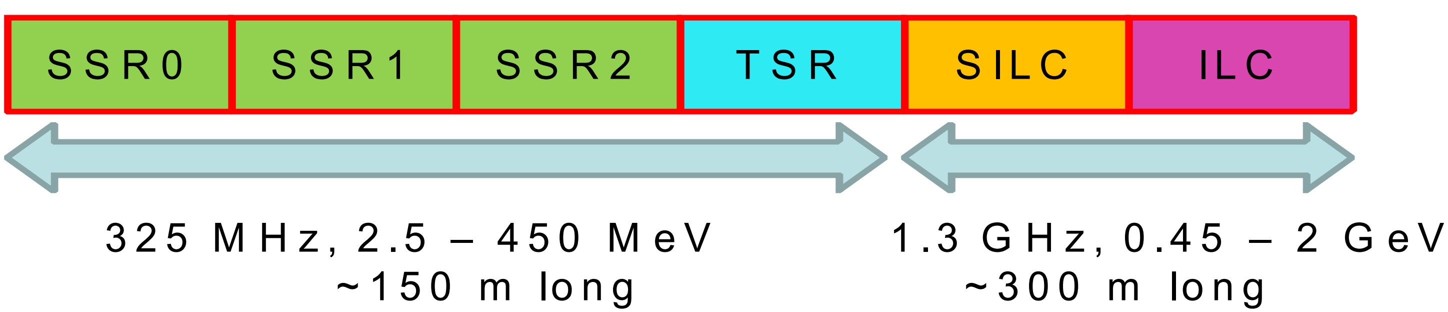


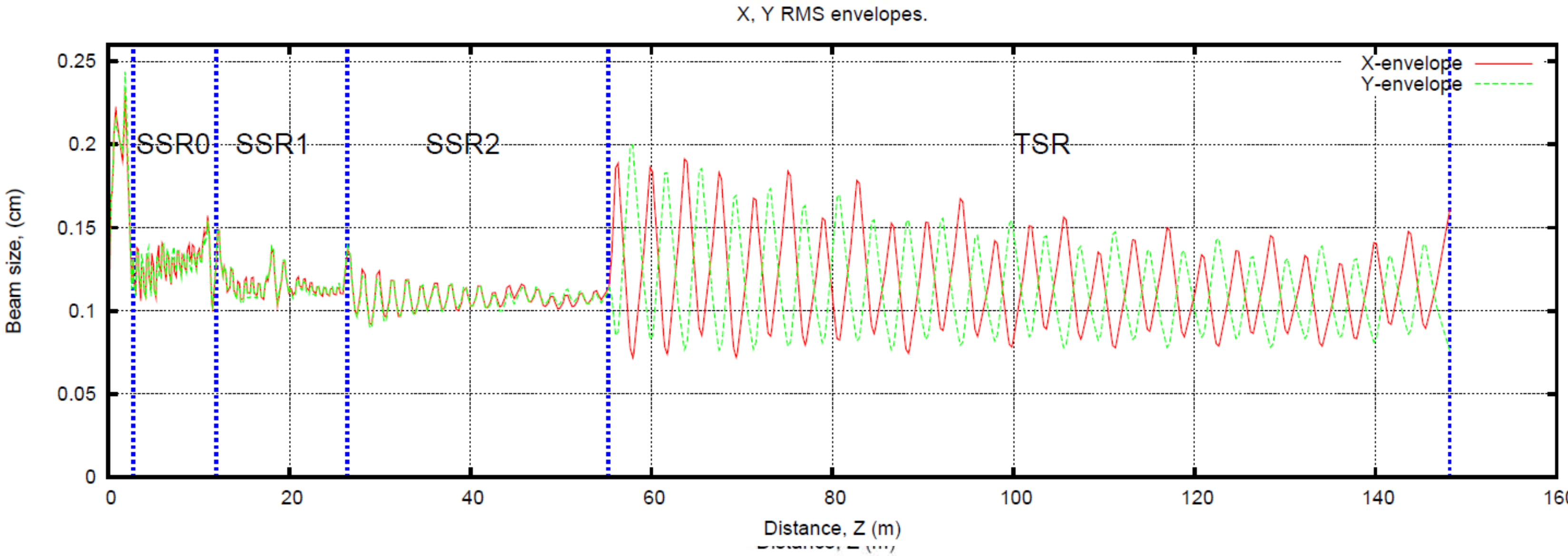
H field

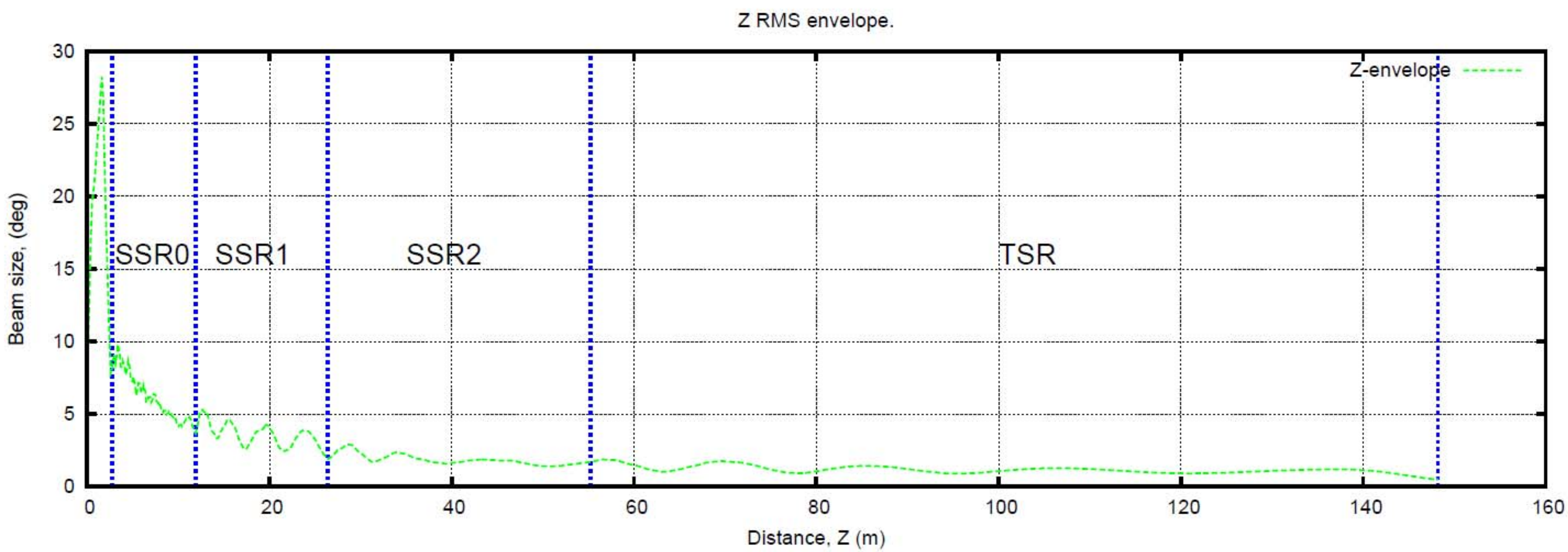
F(MHz)	342.3
R/Q	515
E_{max}/E_{acc}	9.95
H_{max}/E_{acc}	11.3 (mT/MV/m)
$D_{eff}(4^*\beta\lambda/2)$	136mm

Break points for low-energy part, 325 MHz

Section	Energy range MeV	β	Number of cavities/lenses/CM	Type of cavities and focusing element	Power/cavity, kW (I_{av}=1 mA)
Bunching SSR0 (β_G=0.11)	2.5	0.073	2/3/2	Single spoke cavity, Solenoid	0.5
SSR0 (β_G=0.11)	2.5-10	0.073-0.146	16/16/2	Single spoke cavity, Solenoid	0.5
SSR1 (β_G=0.22)	10-32	0.146-0.261	18/18/2	Single spoke cavity, Solenoid	1.3
SSR2 (β_G=0.4)	32-117	0.261-0.5	33/17/3	Single spoke cavity, Solenoid	4.1
TSR (β_G=0.6)	117-466	0.5-0.744	48/48/8	Triple spoke cavity, quads	8.5



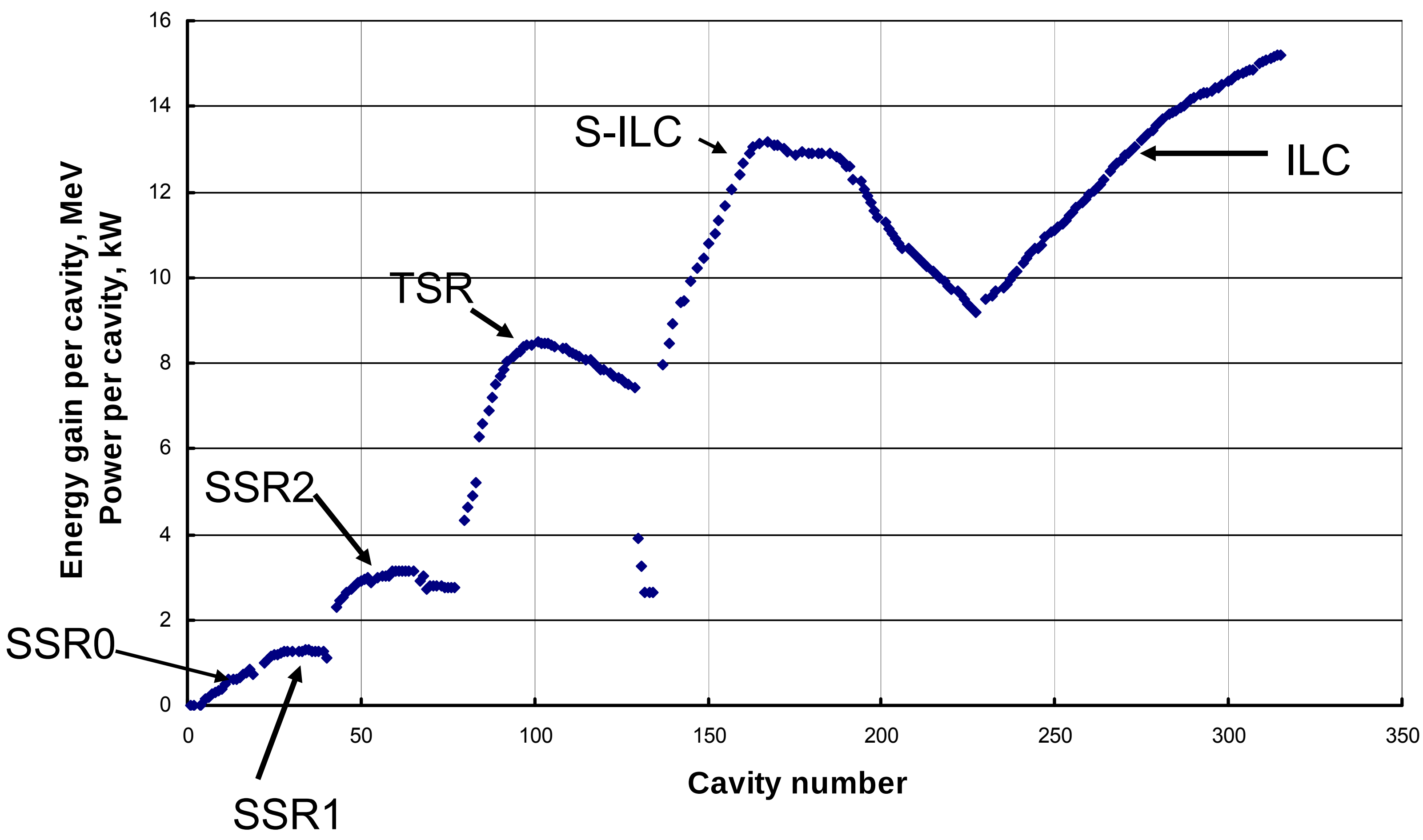

X, Y RMS envelopes.
X-envelope
Y-envelope
SSR0
SSR1
SSR2
TSR
Beam size, (cm)
Distance, Z (m)
0
0.05
0.1
0.15
0.2
0.25
0
20
40
60
80
100
120
140
160


Z RMS envelope.
Z-envelope
SSR0
SSR1
SSR2
TSR
Beam size, (deg)
Distance, Z (m)
0
5
10
15
20
25
30
0
20
40
60
80
100
120
140
160

Parameters of the single cavities SSR1 and SSR2, and triple – spoke cavities TSR.

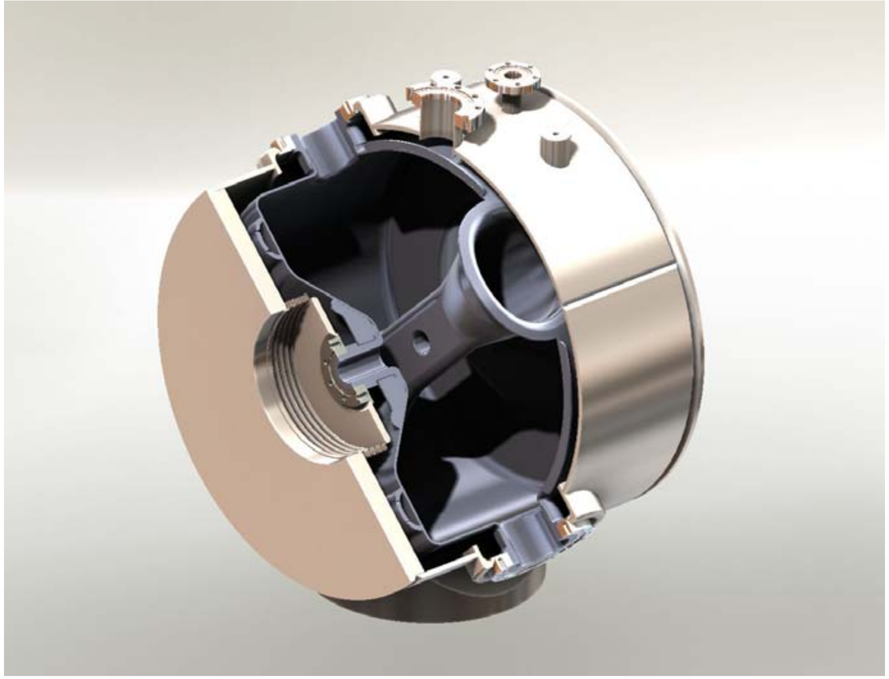
Cavity type	F [MHz]	E_{acc} [MV/m]	L_{eff}, mm	Ep/E_{acc}	B_p/E_{acc} mT/(MV/m)	R/Q Ω	G Ω	$Q_{0,2K}$ $\times 10^9$	$Q_{0,4K}$ $\times 10^9$	P_{2K} [W]	P_{4K} [W]
SSR0	325	8.7	72	4.1	4.6	120	57	9.5	0.7	0.34	4.67
SSR1	325	10.8	135	2.62	3.87	242	84	14.0	1.0	0.63	8.78
SSR2	325	13.6	246	2.42	3.95	322	112	18.0	1.3	1.93	26.74
TSR	325	9.75	943	3.22	6.85	554	117	19.0	1.4	8.03	108.99

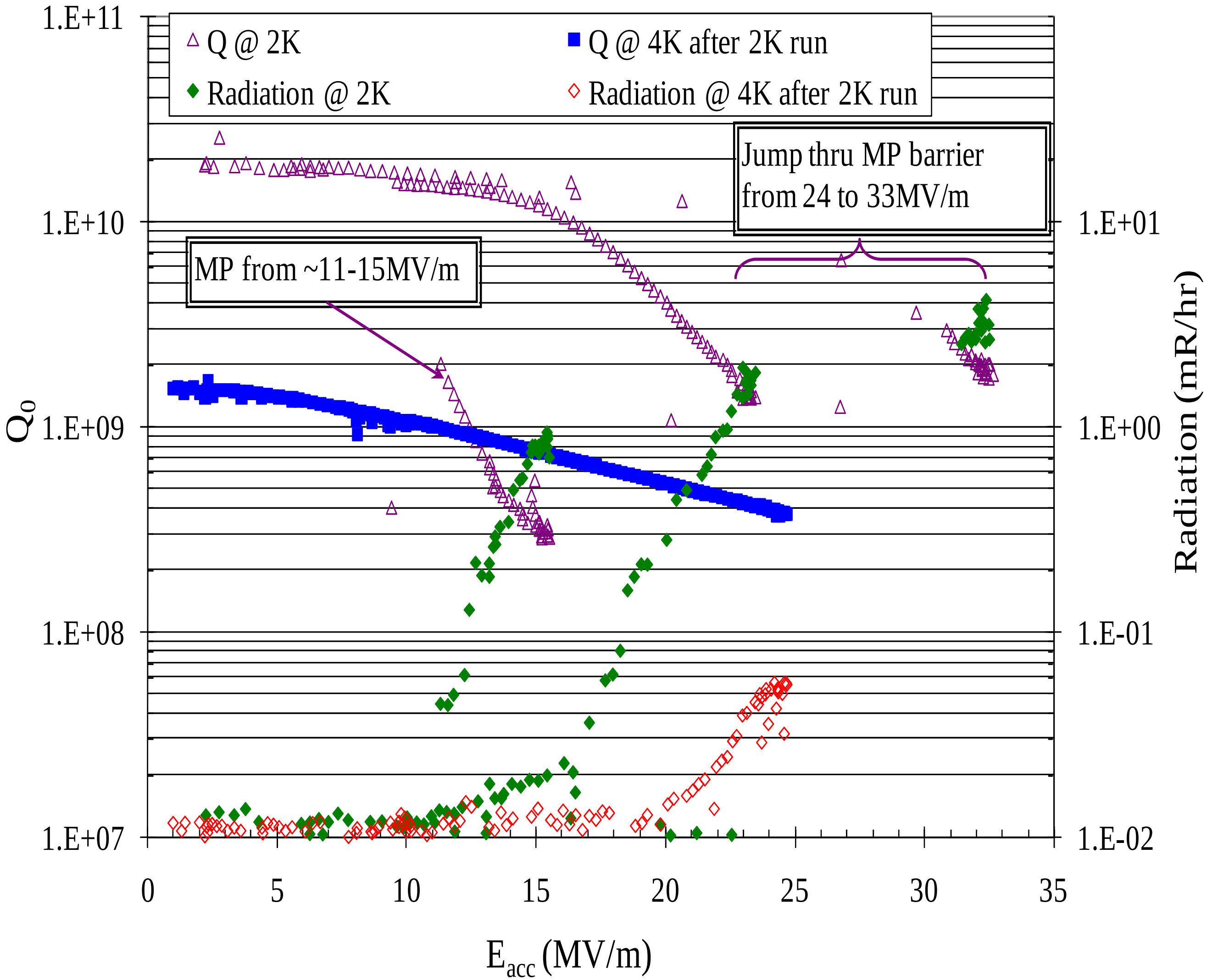
- Surface magnetic field in SSR0 – SSR2 is below 54 mT;
- Surface electric field in SSR0 – SSR2 is below 36 MV/m.



16
14
12
10
8
6
4
2
0
Energy gain per cavity, MeV
Power per cavity, kW
0
50
100
150
200
250
300
350
Cavity number
SSR0
SSR1
SSR2
TSR
S-ILC
ILC

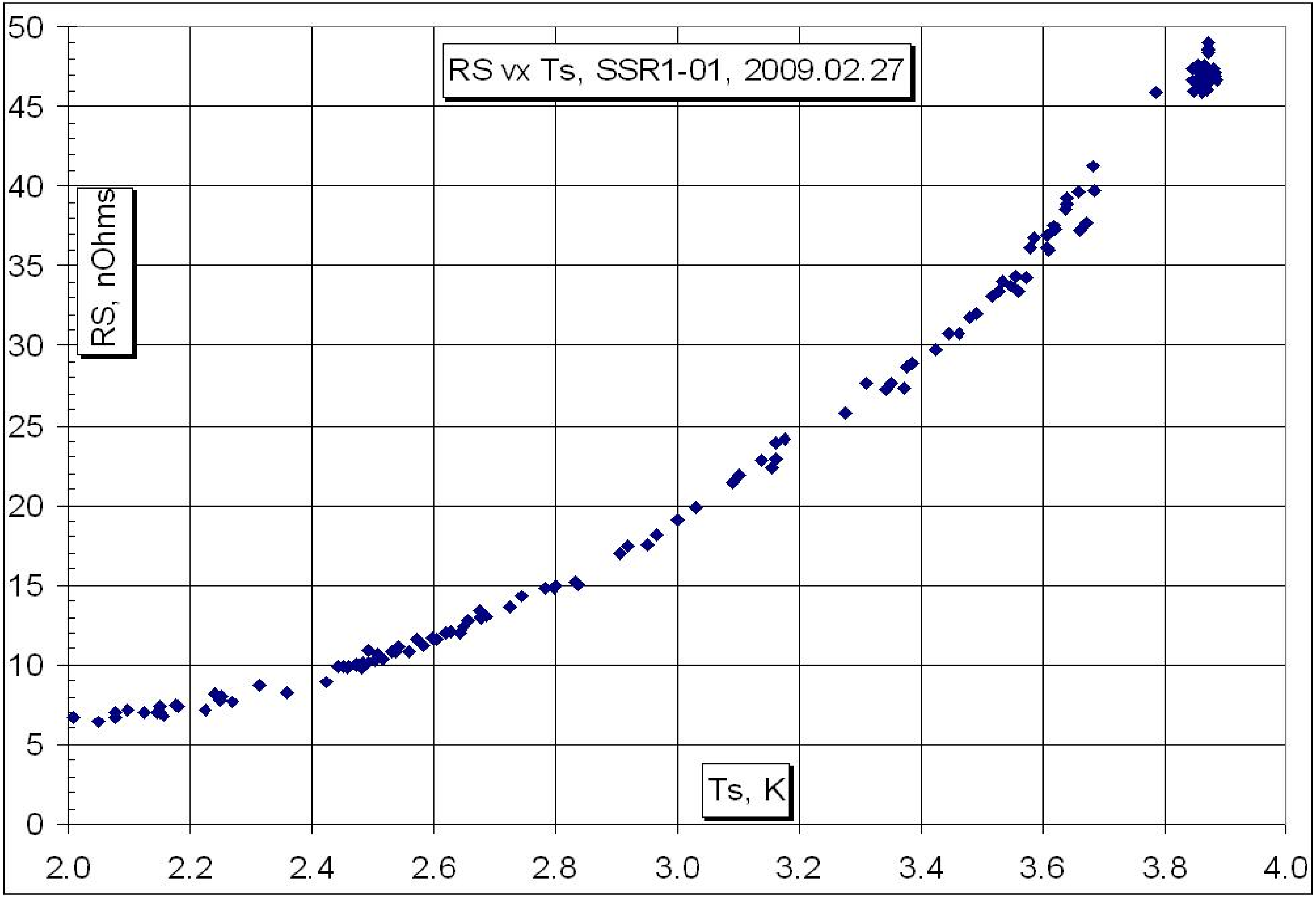
FNAL 325 MHz SSR1 cavity layout and photo. β=0.22



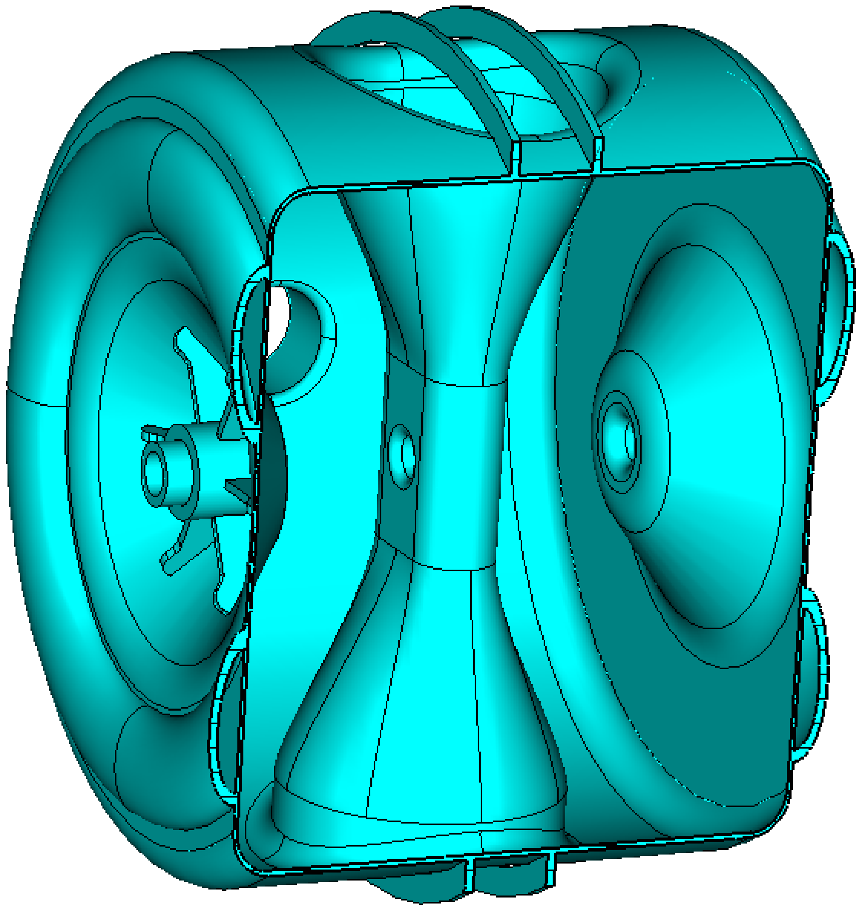


Q0 vs. Eacc from the first cold test of SSR1-02.
Maximal Eacc= 25 MeV/m @4K; 33MeV/m@2K

Spoke Cavity. Surface resistance vs.T



FNAL 325 MHZ SSR2 cavity layout. β=0.4



Conclusions:

- Both single-spoke and half-wave resonators may be used directly in the initial stage of the acceleration instead of RT cavities;

- Present version of the SSR has higher r/Q than the HWR (120 Ohms versus 80 Ohms), but further optimization may reduce the difference;

- Both SSR and HWR may be used in the same structure at 325 MHz and same break points as in HINS;

- Further optimization of the cavity and the structure may reduce the number of cavities;

- Alternating – phase focusing may be helpful (more detailed studies are necessary);

- RF focusing may be used.