Optimisation of single bunch linac for FERMI upgrade

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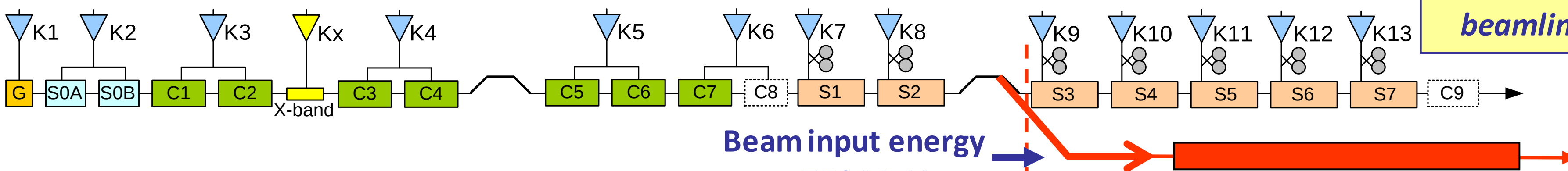
Linac layout and energy ugrading

Motivation from Gerardo D'Auria

Present machine layout

- E_{beam} up to 1.5 GeV
- FEL-1 at 80-20 nm and FEL-2 at 20-4 nm
- Seeded schemes
- Long e-beam pulse (up to 700 fs), with "fresh bunch technique"

FEL-1 & FEL-2 beamlines



Beam input energy ≥ 750 MeV

New FEL beamline $\lambda < 1$ nm

Energy upgrade

• Space available for acceleration	40 m
• Accelerating gradient @12 GHz	60 MV/m
• X-band linac energy gain	2.4 GeV
• Injection energy	.75 GeV
• Linac output energy	3.15 GeV

~50 m available

40 m (80%) available for acceleration

For short bunch (< 100 fs) and low charge (< 100pC) operation

Aperture scaling and BBU

Growth rate of the BBU due to wakefield kick from head to tail:

$$\gamma = \int_0^{L_t} \frac{Ne^2 W'_\perp(s)}{4k_\beta E(z)} dz \Big|^{*}; \quad k_\beta \sim \frac{1}{\langle\beta\rangle}$$

$$W'_\perp(s) = \frac{4Z_0 c}{\pi a^4} s_1 \left(1 - \left[1 + \sqrt{\frac{s}{s_1}}\right] e^{-\sqrt{\frac{s}{s_1}}}\right)^{**}$$

$$\frac{dW'_\perp(s)}{ds} = \frac{4Z_0 c}{\pi a^4} e^{-\sqrt{\frac{s}{s_1}}}$$

$$W'_\perp(\sigma_z) = \frac{dW'_\perp(s)}{ds}\Big|_{s=0} \sigma_z = \frac{4Z_0 c}{\pi a^4}\sigma_z$$

$$E(z) = E_0 + eGz;$$

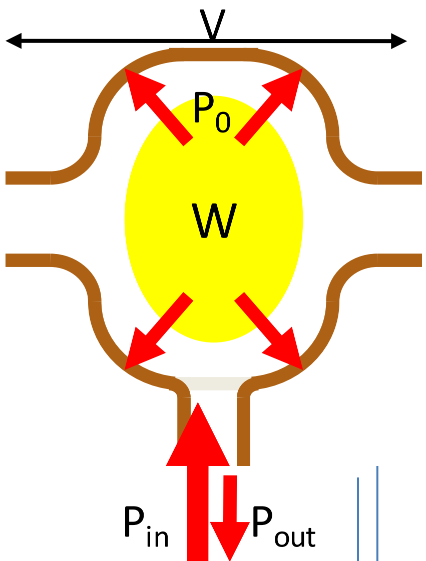
$$\gamma = \frac{Z_0 c}{\pi} \frac{eN\sigma_z}{\langle\beta\rangle a^4 G} \ln\left(\frac{E_L}{E_0}\right)$$

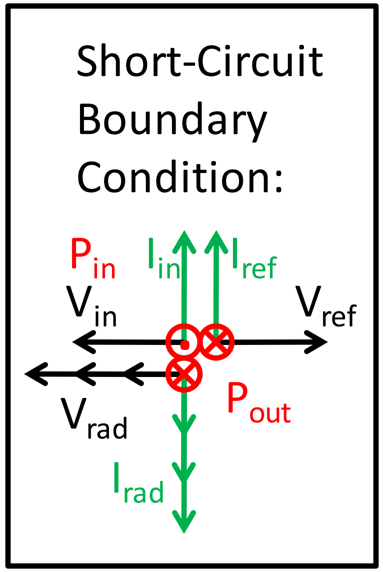
	Present	Upgrade	Scaling factor γ'/γ
L_t [m]	40	40	
<β> [m]	~10	~10	
E_0 [GeV]	0.75	0.75	
E_L [GeV]	1.5	3.15	1/2
σ_z [fs]	700	100	1/7
eN [pC]	500	100	1/5
			↓
a [mm]	5	5*0.35=**1.75** ←	1/(2*7*5)
γ	0.02	0.02	Keep const

* Alex Chao, "Physics of collective beam instabilities in high energy accelerators", 1993

** Karl Bane, "Short-range Dipole Wakefields in Accelerating structures for the NLC", SLAC-PUB-9663, 2003

Transient in a cavity -> pulse compression





$$P_{out} = P_{in}(t=0)\left(\frac{V_{out}}{V_{in}}\right)^2$$

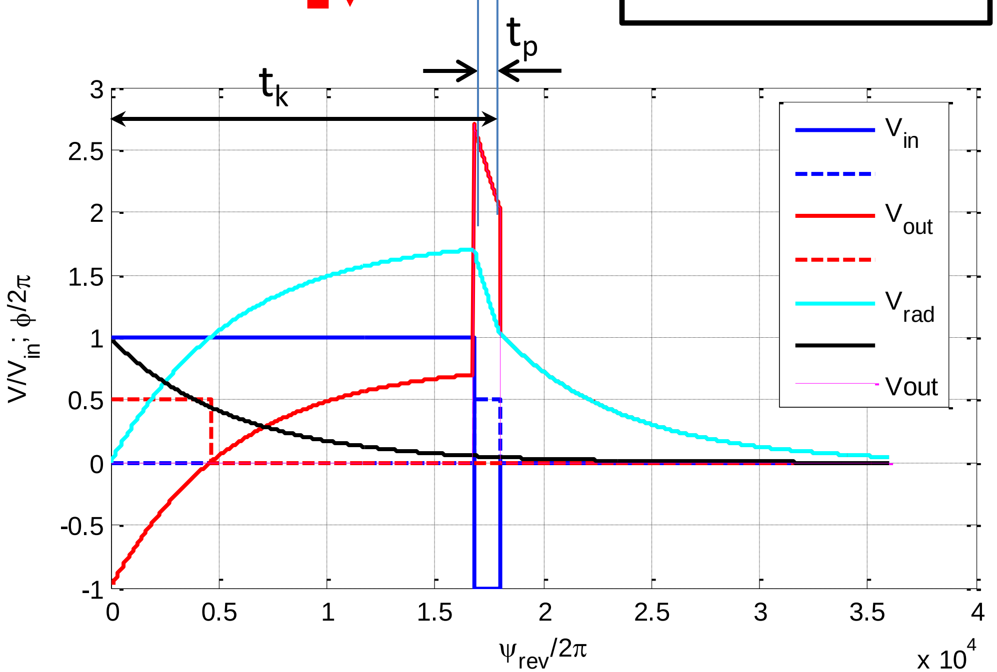
$$V_{out} = V_{rad} + V_{ref} = V_{rad} - V_{in}$$

$$V_{rad} = (V_{in} * C_{resp})$$

$$V_{in} = V_{in}(t=0)\exp(\omega t)$$

$$C_{resp} = \frac{1}{Q_e}\exp\left(-\frac{\omega_0 t}{2Q_l}\right)$$

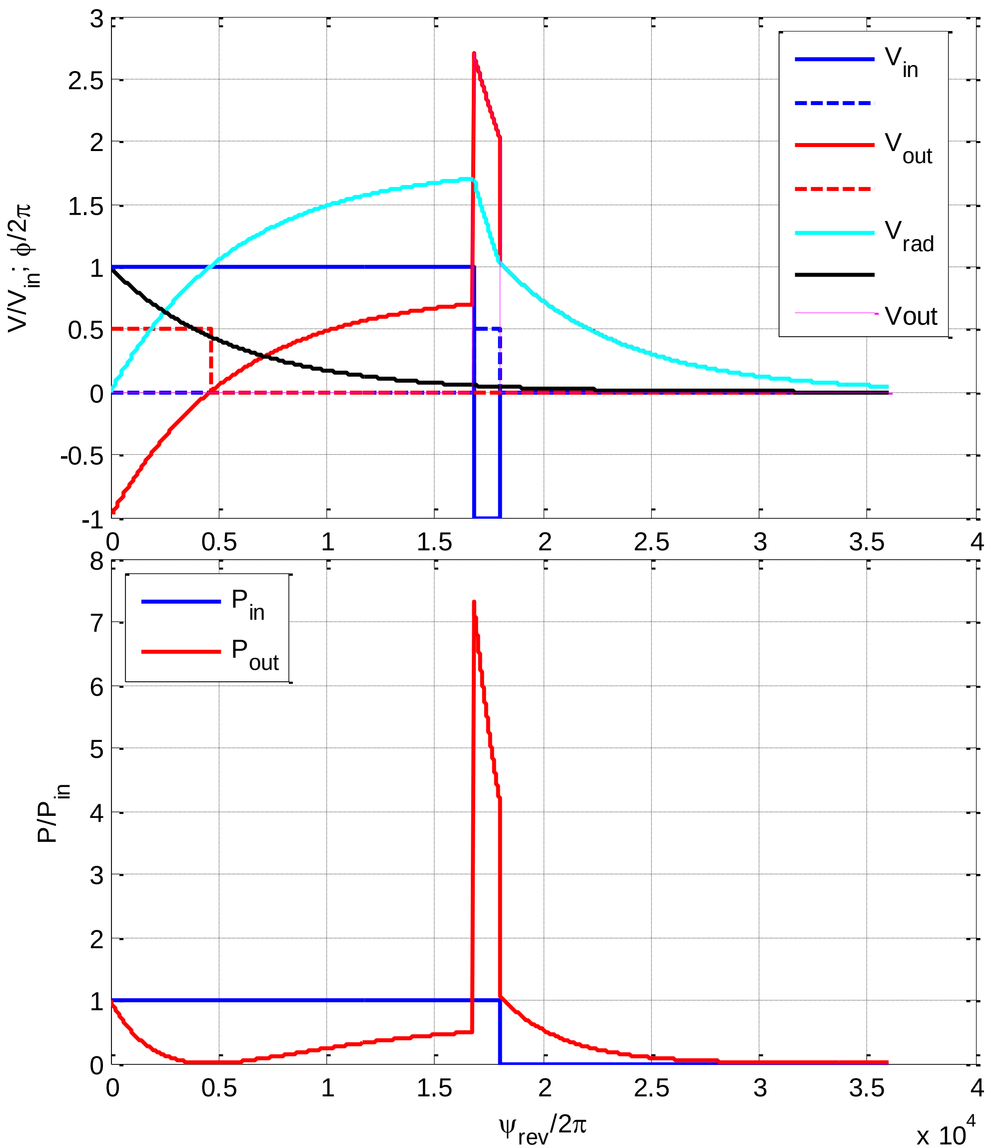
$$Q_l = \frac{Q_0 Q_e}{Q_0 + Q_e}$$



Analytical expression for the pulse shape

$$\left.\frac{V_{out}}{V_{in}}(t)\right|_{t_0=t_k-t_p}^{t_k} = f(\omega=\omega_0; t_k; t_p; Q_0; Q_e)$$

Pulse compression: example



Example at 12 GHz:

Q_0 = 180000; Q_e = 20000
t_k = 1500 ns klystron pulse length
t_p = 100 ns compressed pulse length

Average power gain =
= average power in compressed pulse / input power = 5.6
Average power efficiency =
= compressed pulse energy / input pulse energy = 34.7 %

Effective shunt impedance of Acc. Structure + Pulse Compressor

Time - dependent gradient*: $G(z,t') = G_0[t' - \tau(z)]g(z);$

$$\tau(z) = \int_0^z \frac{dz'}{v_g(z')}; \quad t_f = \tau(L_s); \quad t' = t - t_0$$

$$G_0(t') = \sqrt{\frac{\omega}{v_{g0}} \frac{R}{Q} P_{out}(t')} = \sqrt{\frac{\omega}{v_{g0}} \frac{R}{Q} P_{in}} \frac{V_{out}}{V_{in}}(t')$$

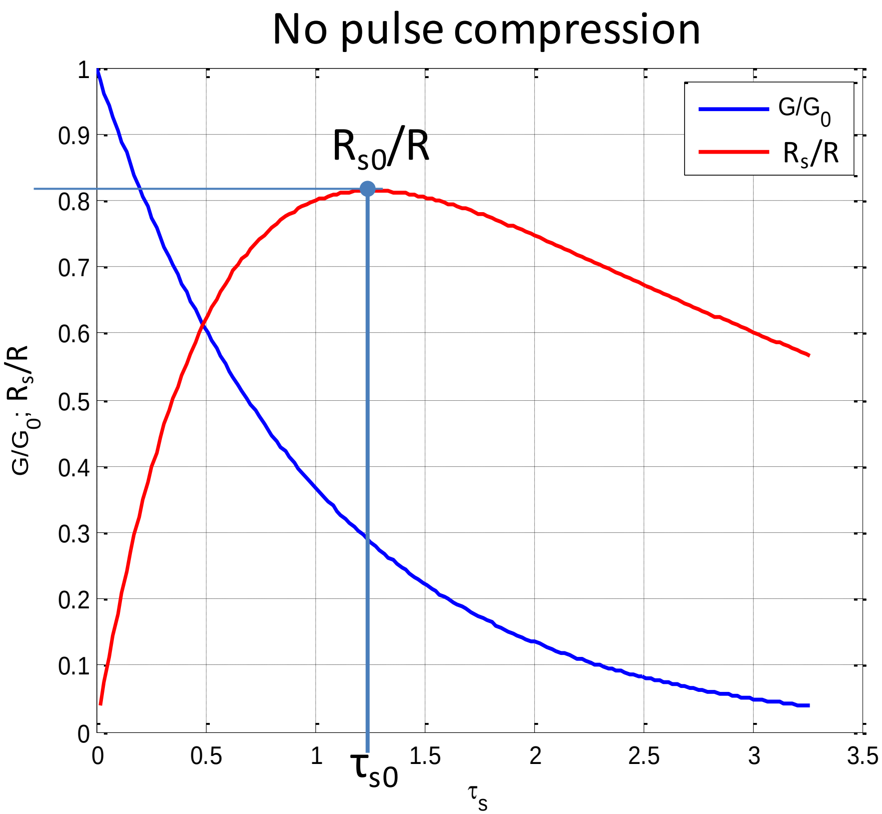
$$V_a = \int_0^{L_s} dz' G(z', t' = t_f = t_p); \quad \tau_s = \alpha L_s = \frac{\omega}{2 v_g Q} L_s$$

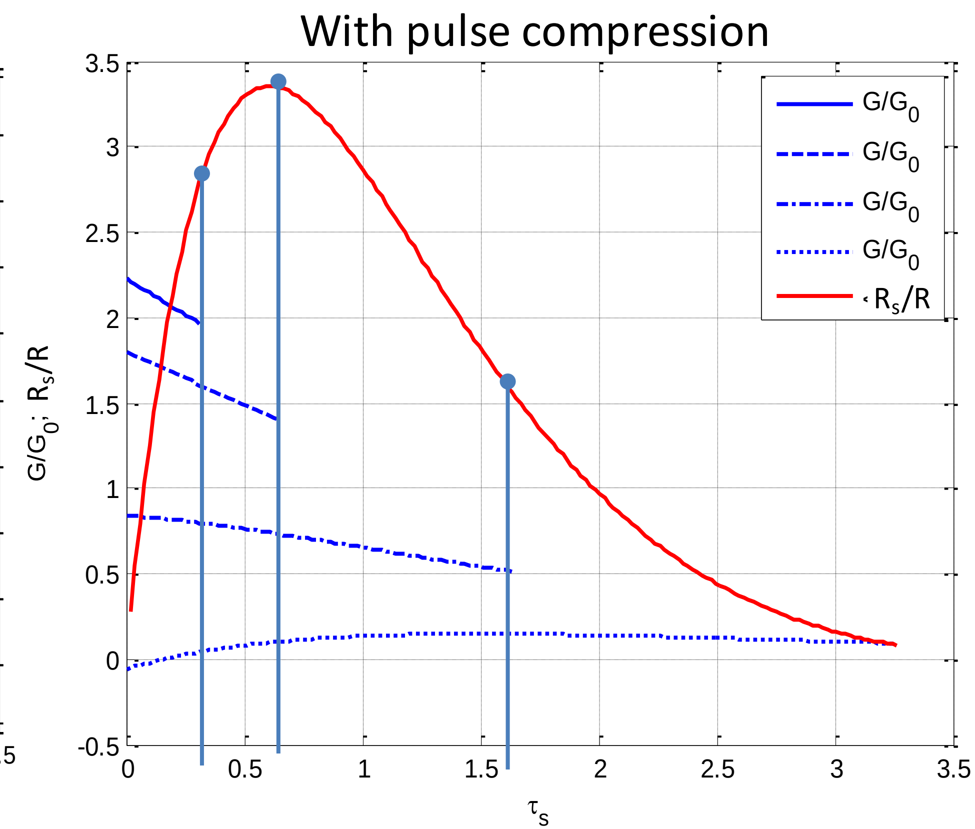
Effective shunt impedance**: $R_s = \frac{V_a^2}{P_{in} L_s} [\Omega / m]; \quad P_{tot} = \frac{V_{tot} \langle G \rangle}{R_s}$

* i.e. A. Lunin, V. Yakovlev, A. Grudiev, PRST-AB 14, 052001, (2011)

** R. B. Neal, Journal of Applied Physics, V.29, pp. 1019-1024, (1958)

Effective Shunt impedance in Const Impedance (CI) AS





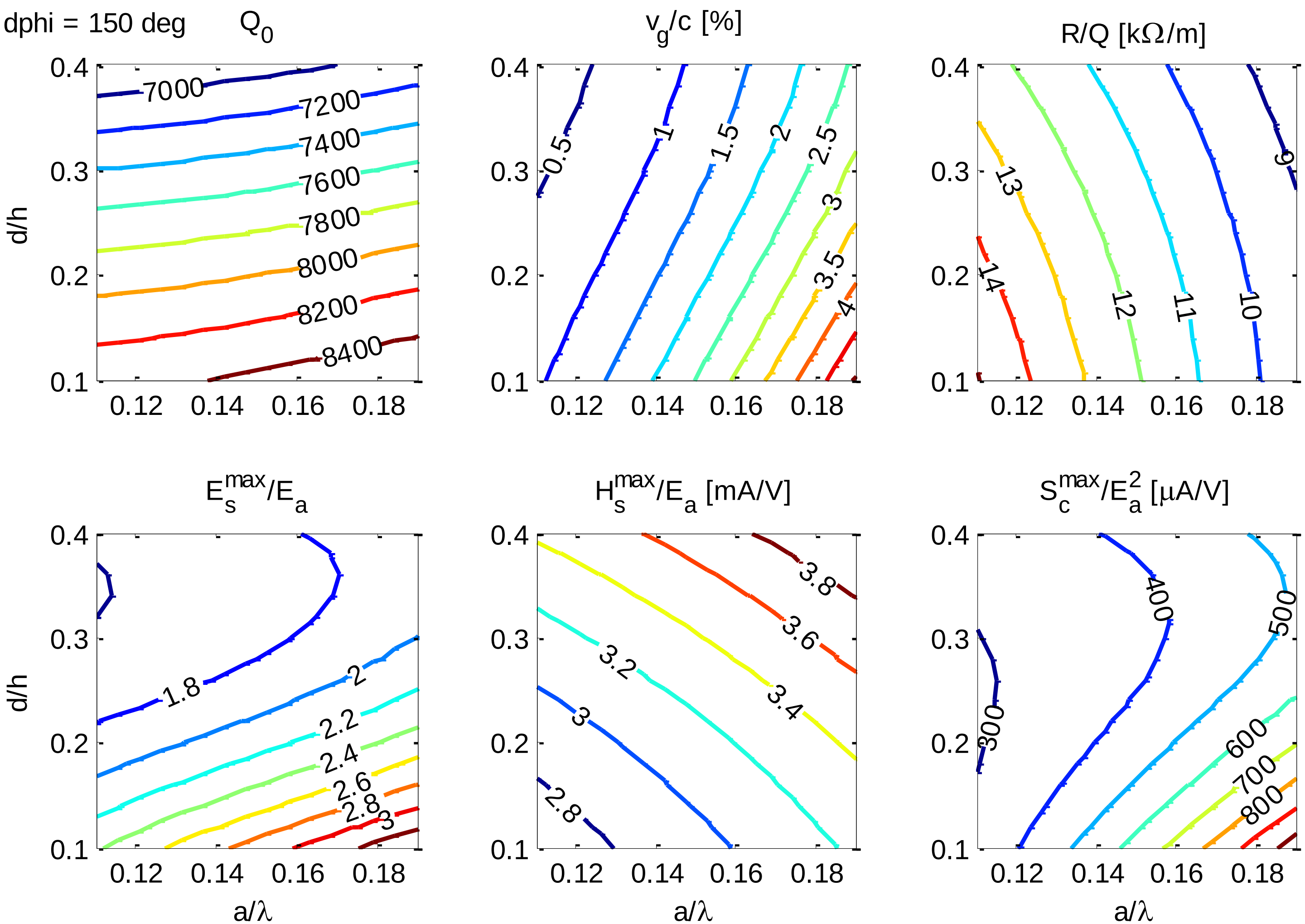
$\tau_{s0} = 1.2564 \Rightarrow R_{s0}/R = 0.8145$

For $Q = 8128$; $Q_0 = 180000$; $Q_e = 20000$

$\tau_{s0} = 0.6078 \Rightarrow R_{s0}/R = 3.3538$

But in general it is function all 3 Qs: Q, Q_0, Q_e

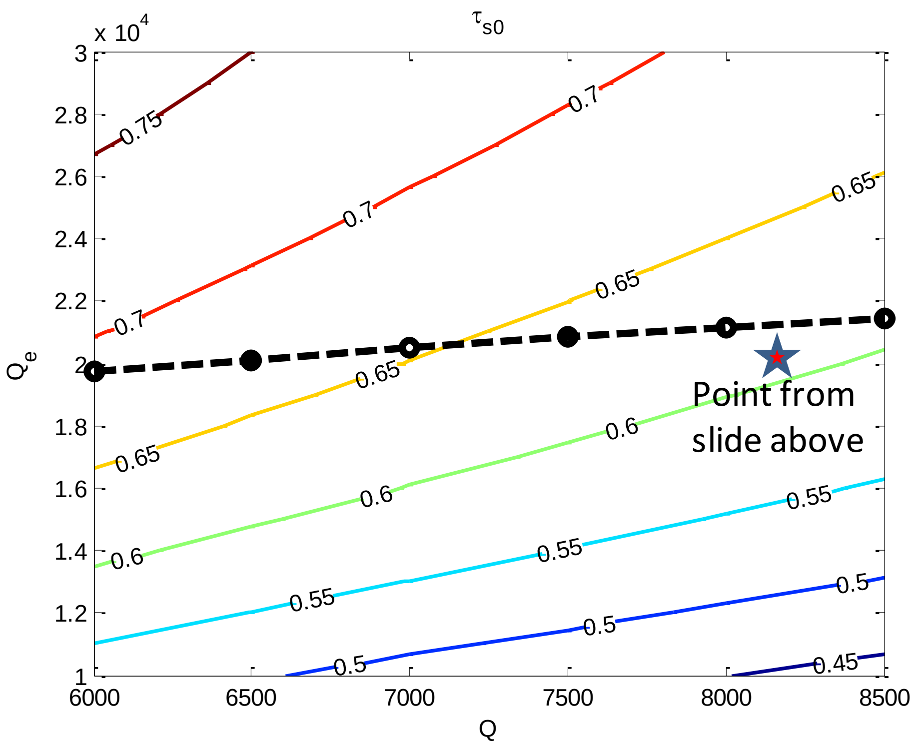
Undamped cell parameters for dphi=150º



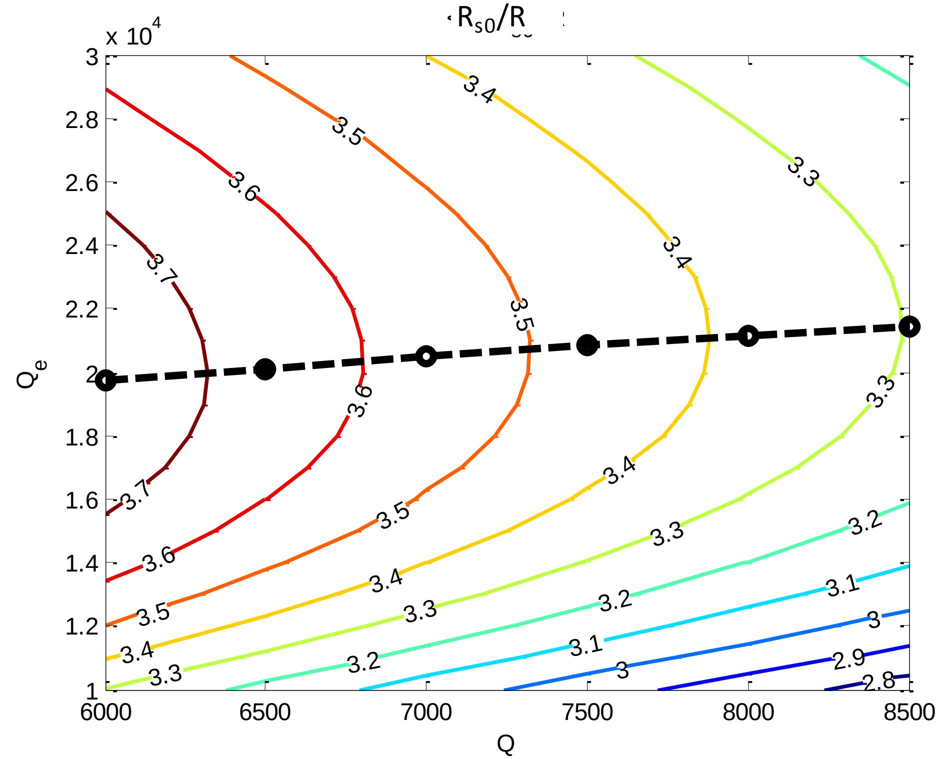
CIAS pulse compression optimum

Q_0 = 180000 – Q-factor of the pulse compressor cavity(s)
t_k = 1500 ns – klystron pulse length

Optimum attenuation: τ_{s0}



Averaged Shunt Impedance R_{s0}/R

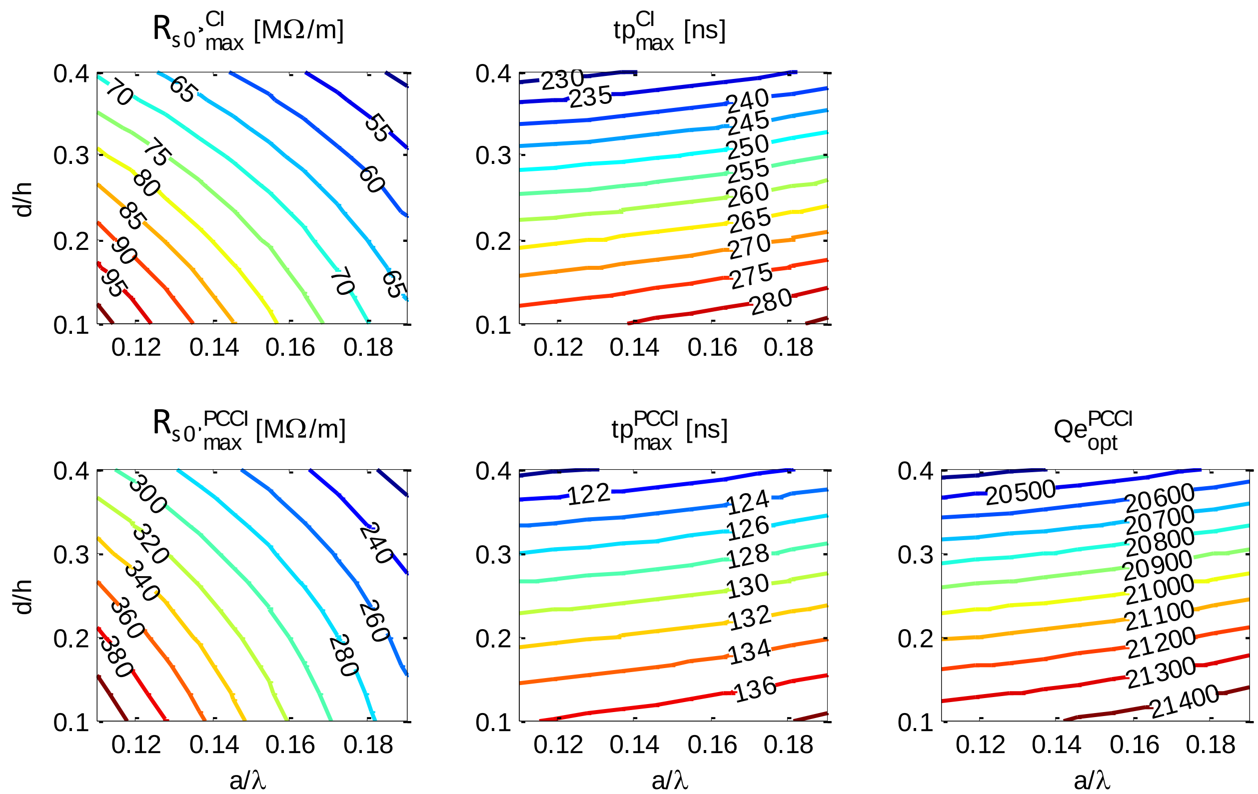


Optimum value of Q_e ~ const: ranges from 20000 for Q=6000 up to 21000 for Q=8000

CIAS Effective Shunt Impedance: w/o and with pulse compression

No pulse compression

With pulse compression



- As expected ~ 4 times higher effective shunt impedance with pulse compression
- Optimum pulse length is ~ two times longer no pulse compression is used, still it is much shorter than the klystron total pulse length

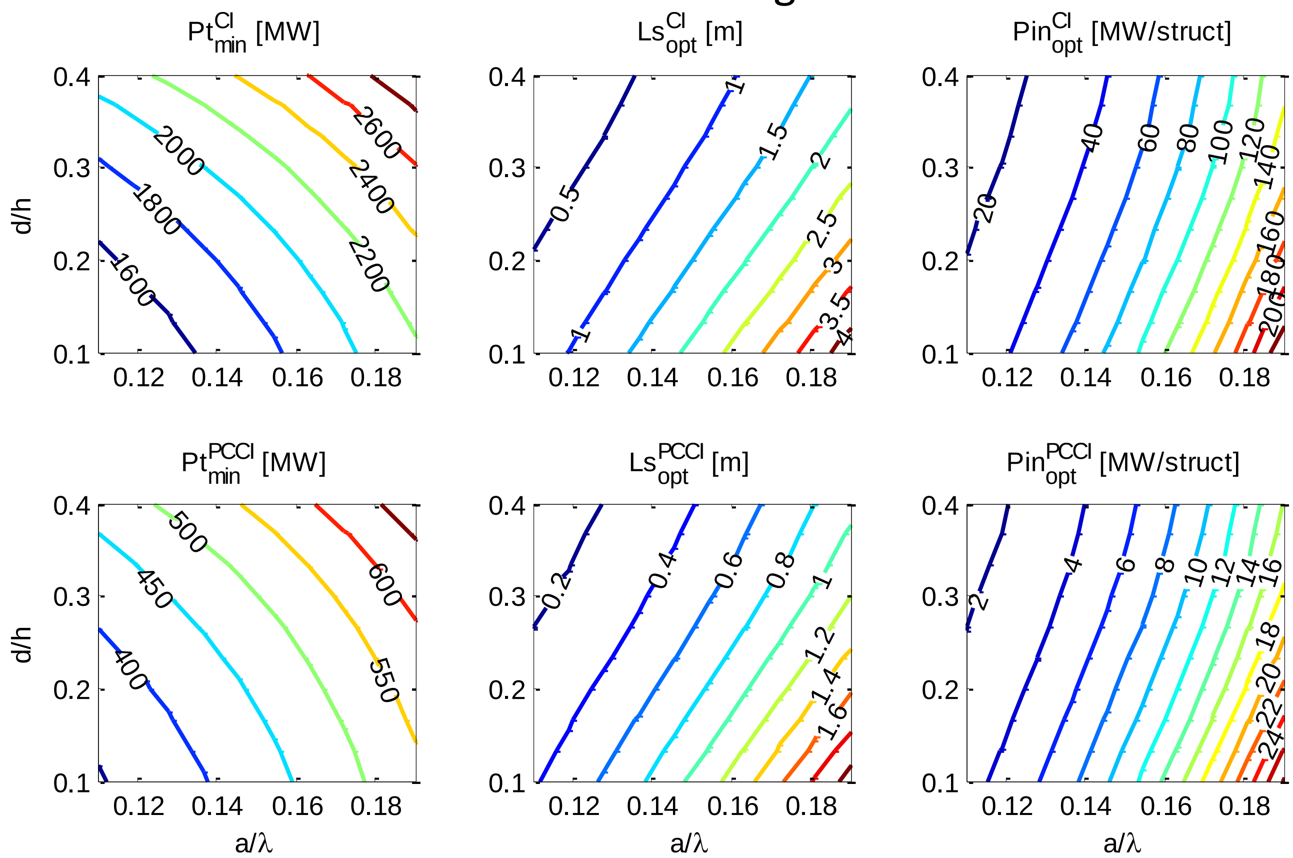
CIAS linac 40 m long, <G>=60MV/m : w/o and with PC

Total klystron power

Optimum structure length

Klystron power per structure

~# of structures per 0.8x50 MW klystron

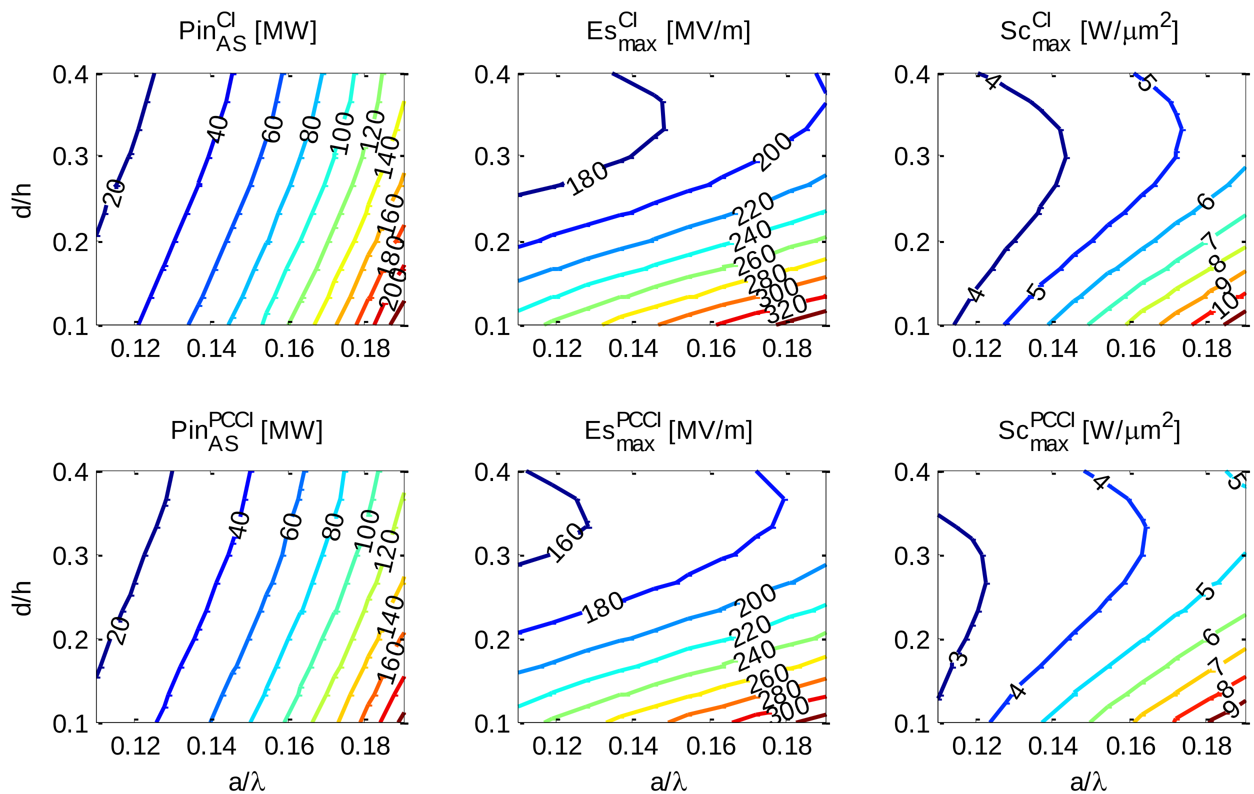


2 -> 1/5

~20 -> ~2

CIAS high gradient related parameters: w/o and with PC

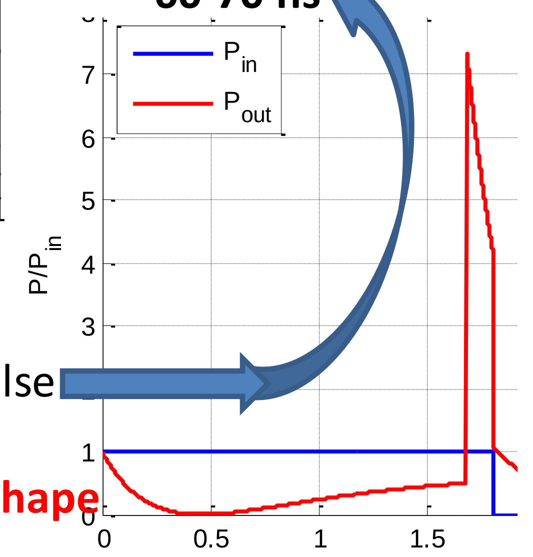
AS Pin(t=0) | AS Esurf(z=0,t=0) | AS Sc(z=0,t=0)



Typical Pulse length

Flat pulse: 230-290 ns
Above the HG limits for larger apertures

Peaked pulse:
122-136 ns
60-70 ns



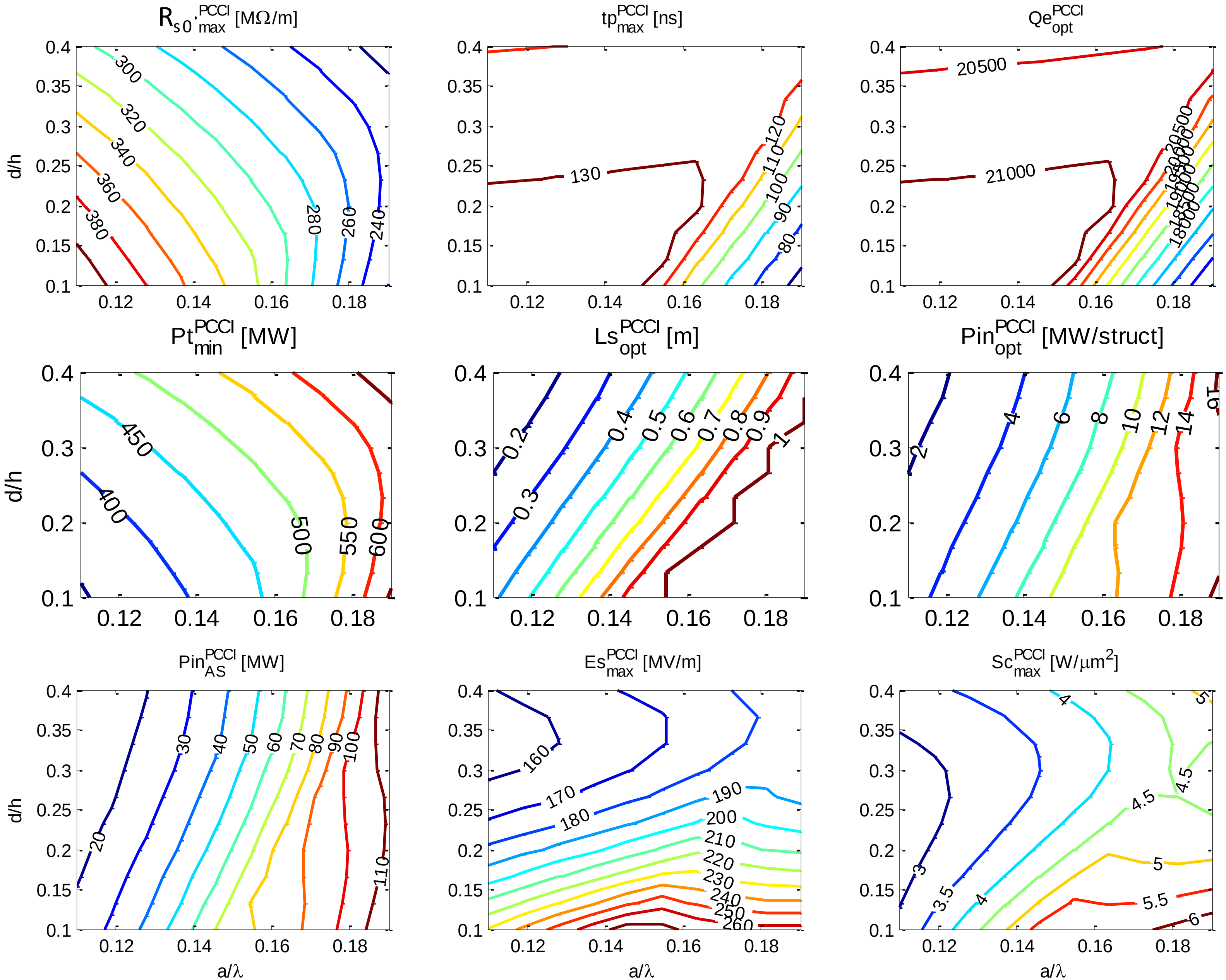
Assamption:

Effective pulse length for breakdowns is ~ half of the compressed pulse

⇒ Breakdown limits are very close for large a/λ and thin irises

A dedicated BDR measurements are needed for compressed pulse shape

CIAS with PC: max. Lstruct < 1m

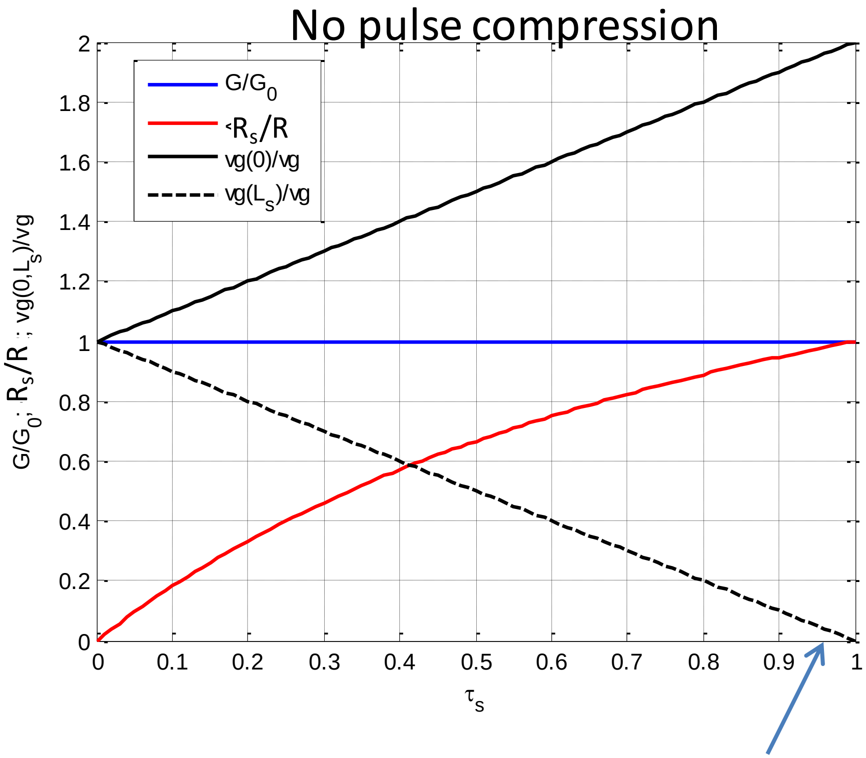


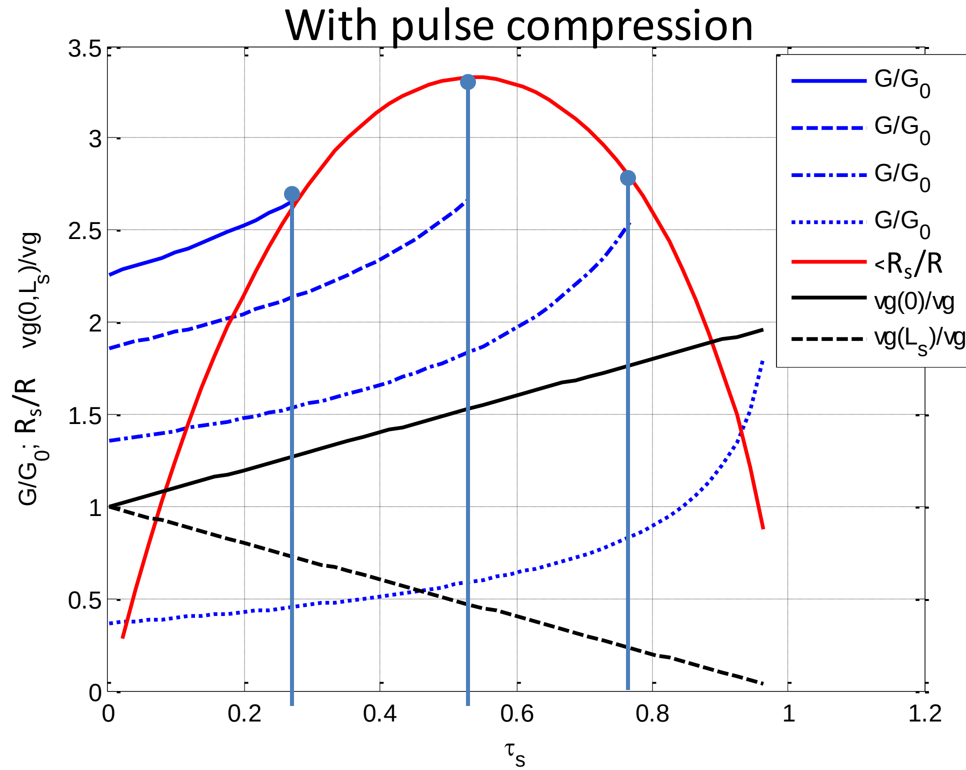
For high vg corner
Shorter tp
Lower Qe

More Ptotal
Less Pin/klyst.

Lower field and power quantities

Const Gradient (CG) AS





If the last cell ohmic and diffraction losses are equal => minimum vg.

For 12 GHz, Q=8000, l_c = 10mm: τ_{s0} = 0.96;

min(vg/c) = 0.032 - very low vg at the end

BUT CGAS can reach higher R_s/R than CIAS

Lowest group velocity limits the CGAS performance

Q = 8128; Q0 = 180000; Qe = 20000

τ_{s0} = 0.5366 => R_{s0}/R = 3.328 – function Q-factors

Roughly the same as for CIAS with pulse compression

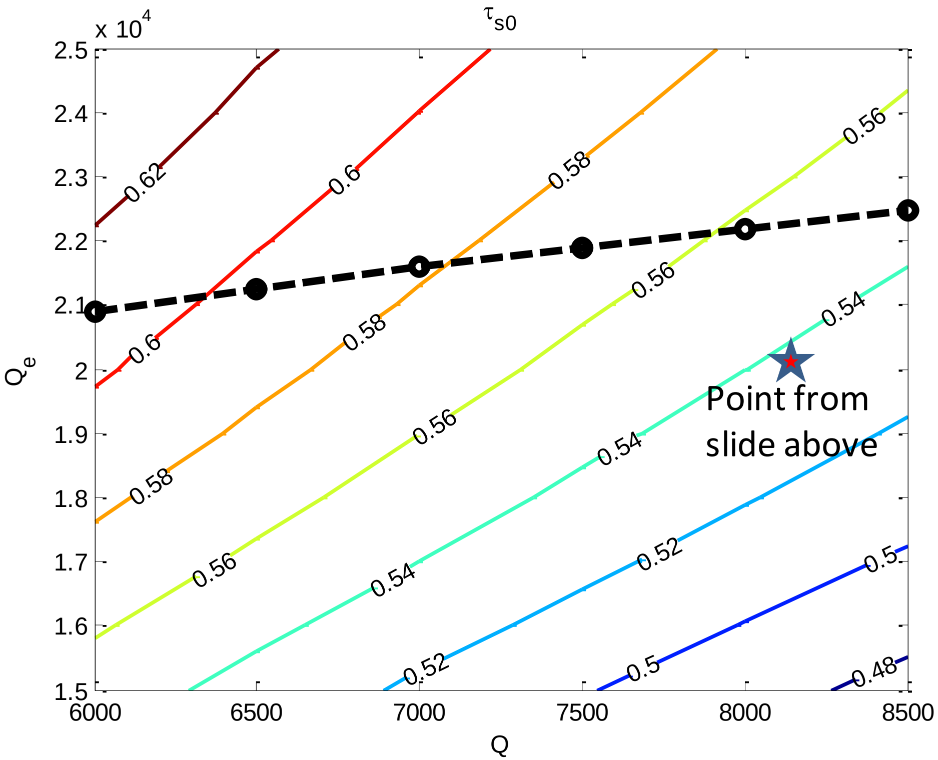
vg_max = vg(1+0.5366); vg_min = vg(1-0.5366)

Optimum vg variation is about factor 3.3

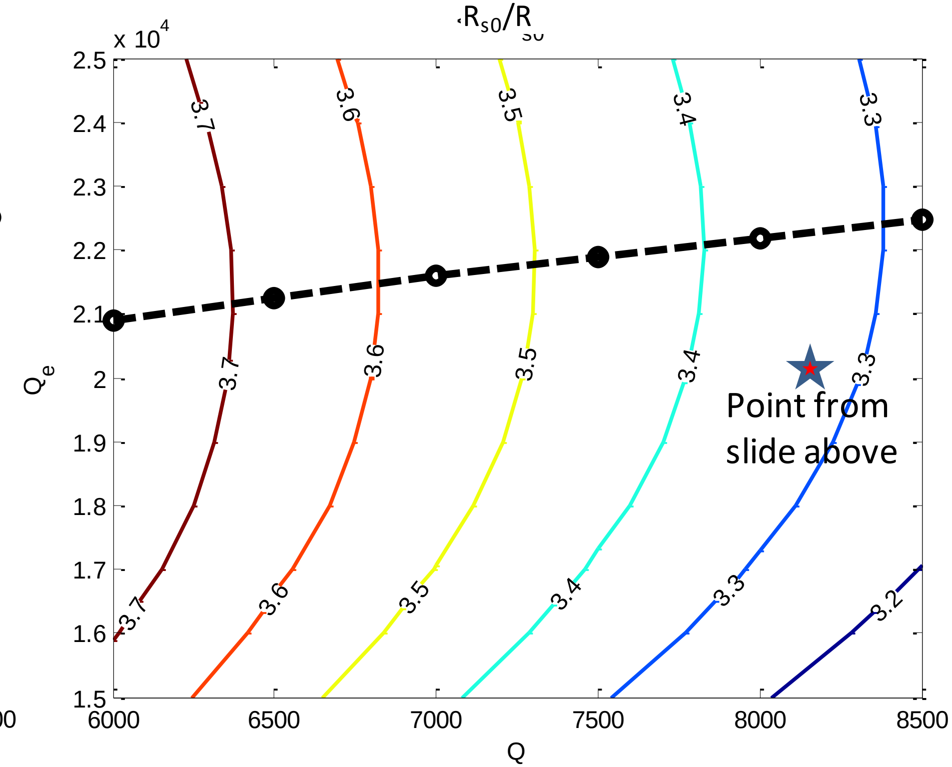
CIAS pulse compression optimum

Q_0 = 180000 – Q-factor of the pulse compressor cavity(s)
t_k = 1500 ns – klystron pulse length

Optimum attenuation: τ_{s0}



Averaged Shunt Impedance R_{s0}/R

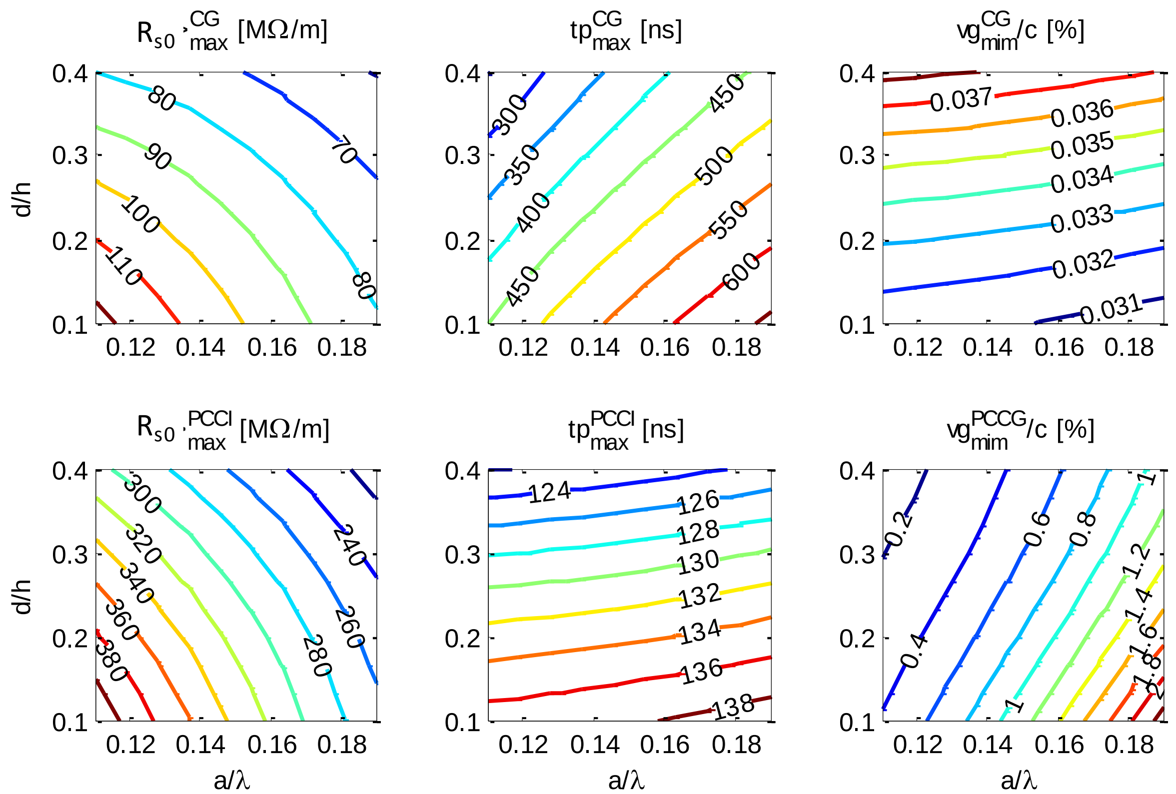


Optimum value of Q_e ~ const: ranges from 21000 for Q=6000 up to 22000 for Q=8000

CGAS Effective Shunt Impedance: w/o and with pulse compression

No pulse compression

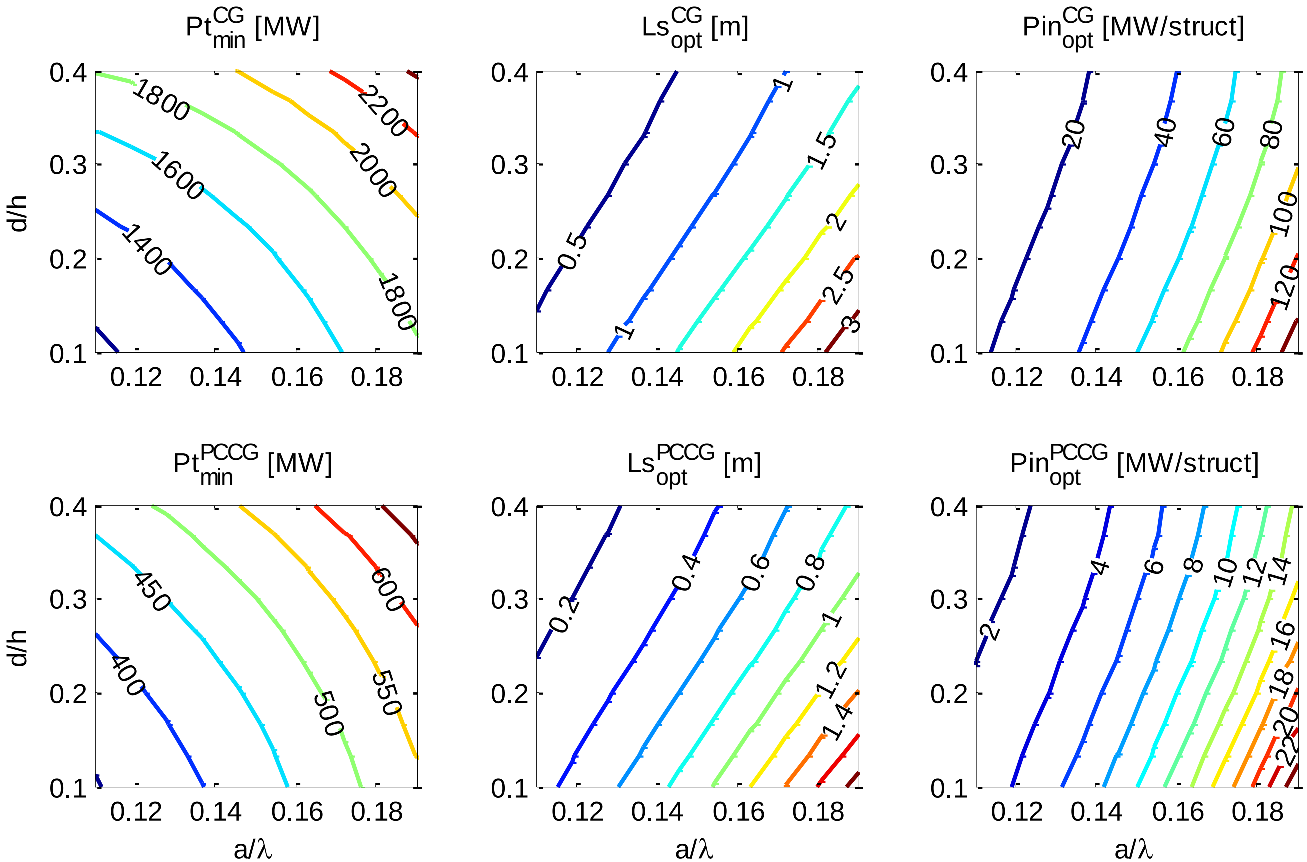
With pulse compression



- CGAS has higher R_s compared to CIAS if no pulse compression is used and the **same R_s with pulse compression**
- Optimum pulse length is ~ 4.5 times longer if no pulse compression is used, still it is significantly shorter than the klystron total pulse length

CGAS linac 40 m long, <G>=60MV/m : w/o and with PC

Total klystron power	Optimum structure length	Klystron power per structure	~# of structures per 0.8x50 MW klystron



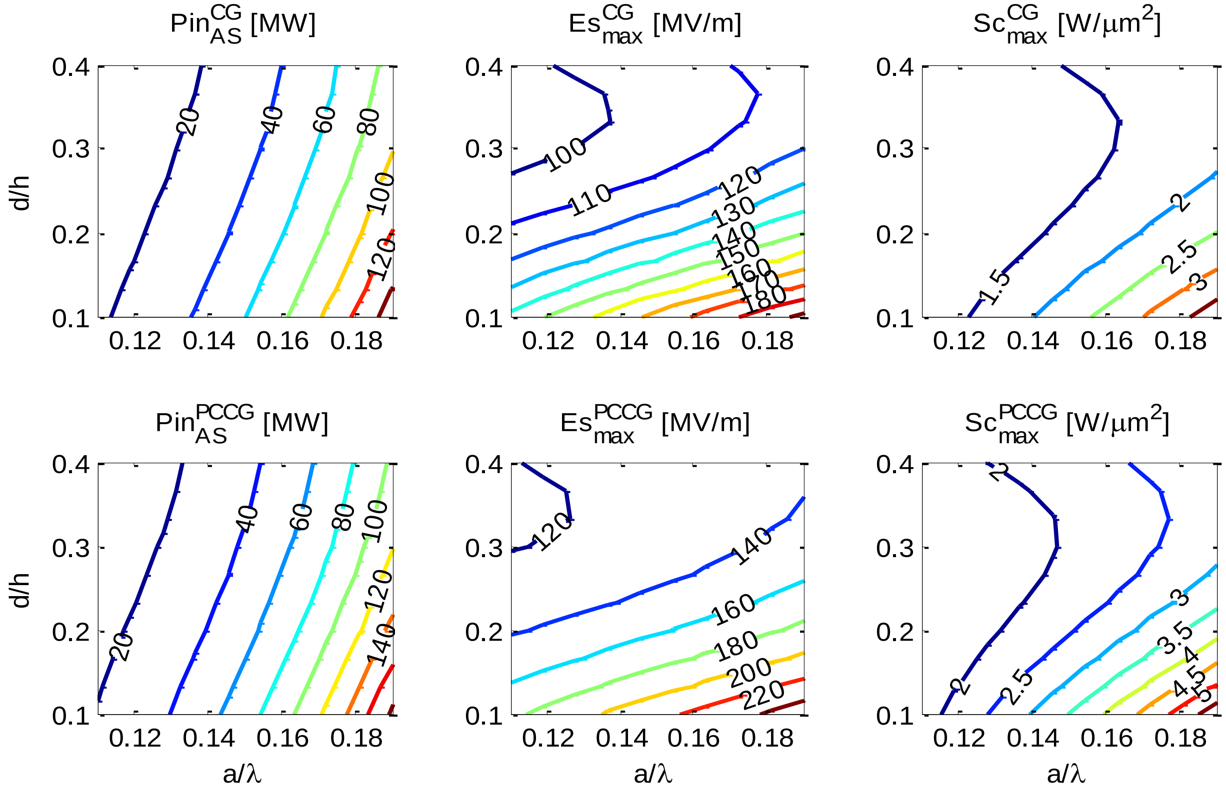
2 -> 1/3

~20 -> ~2

Optimum structure length and input power per structure are very similar to the CIAS

CGAS high gradient related parameters: w/o and with PC

AS Pin(t=0) | AS Esurf(z=0,t=0) | AS Sc(z=0,t=0)



Typical Pulse length

Flat pulse: 250-650 ns
Above the HG limits for larger apertures

Peaked pulse:
122-138 ns
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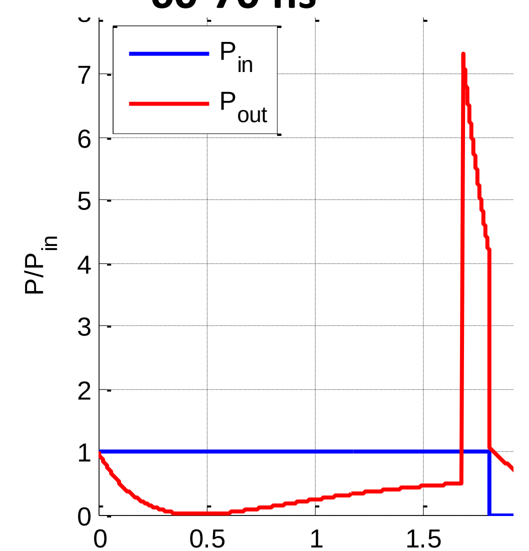
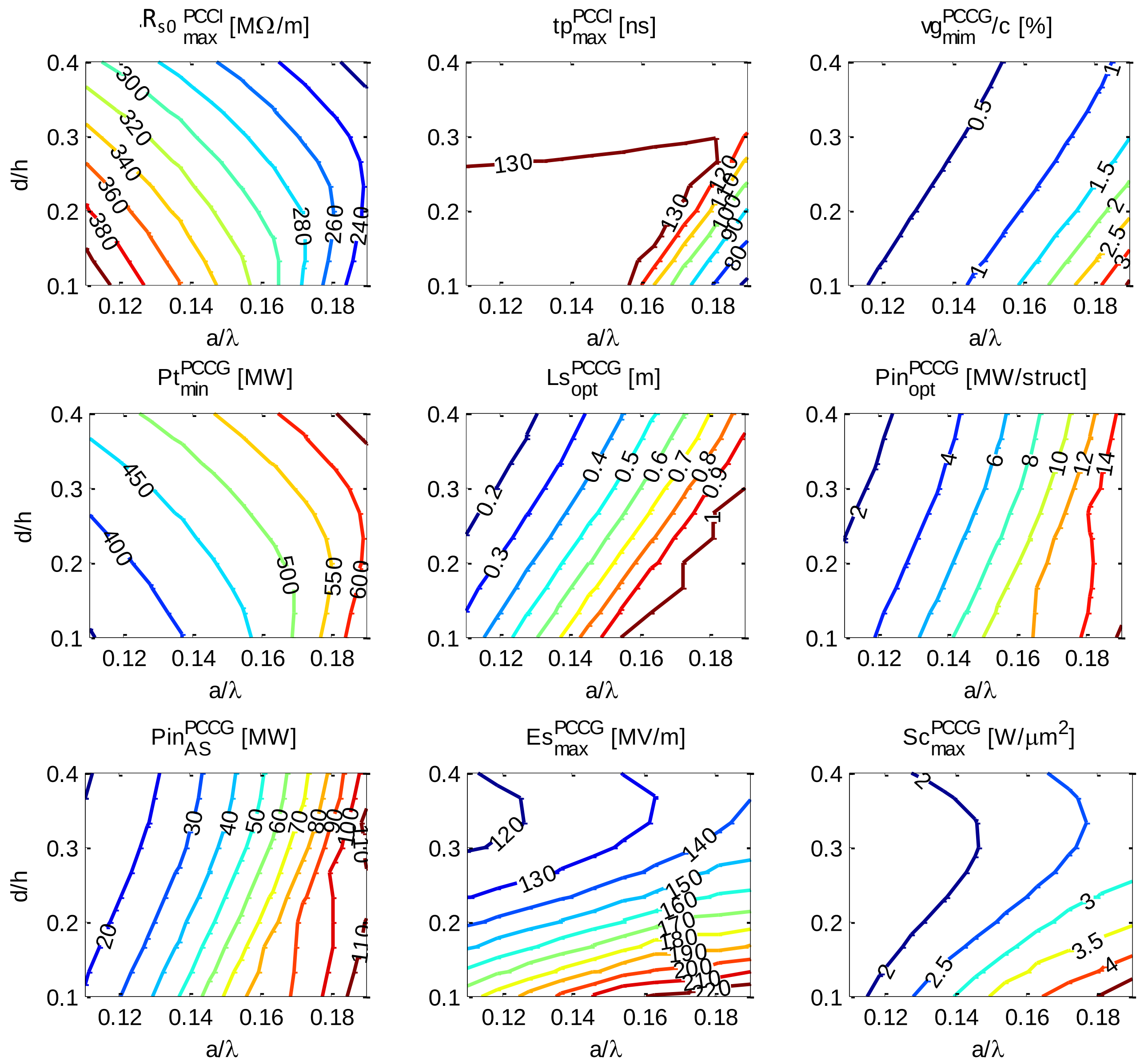


- Due to much shorter **compressed pulse the CGAS with PC is safer** in terms of high gradient related parameters than w/o PC
- Also due to CG profile it is significantly safer than CIAS with PC

CGAS with PC: max. Lstruct < 1m



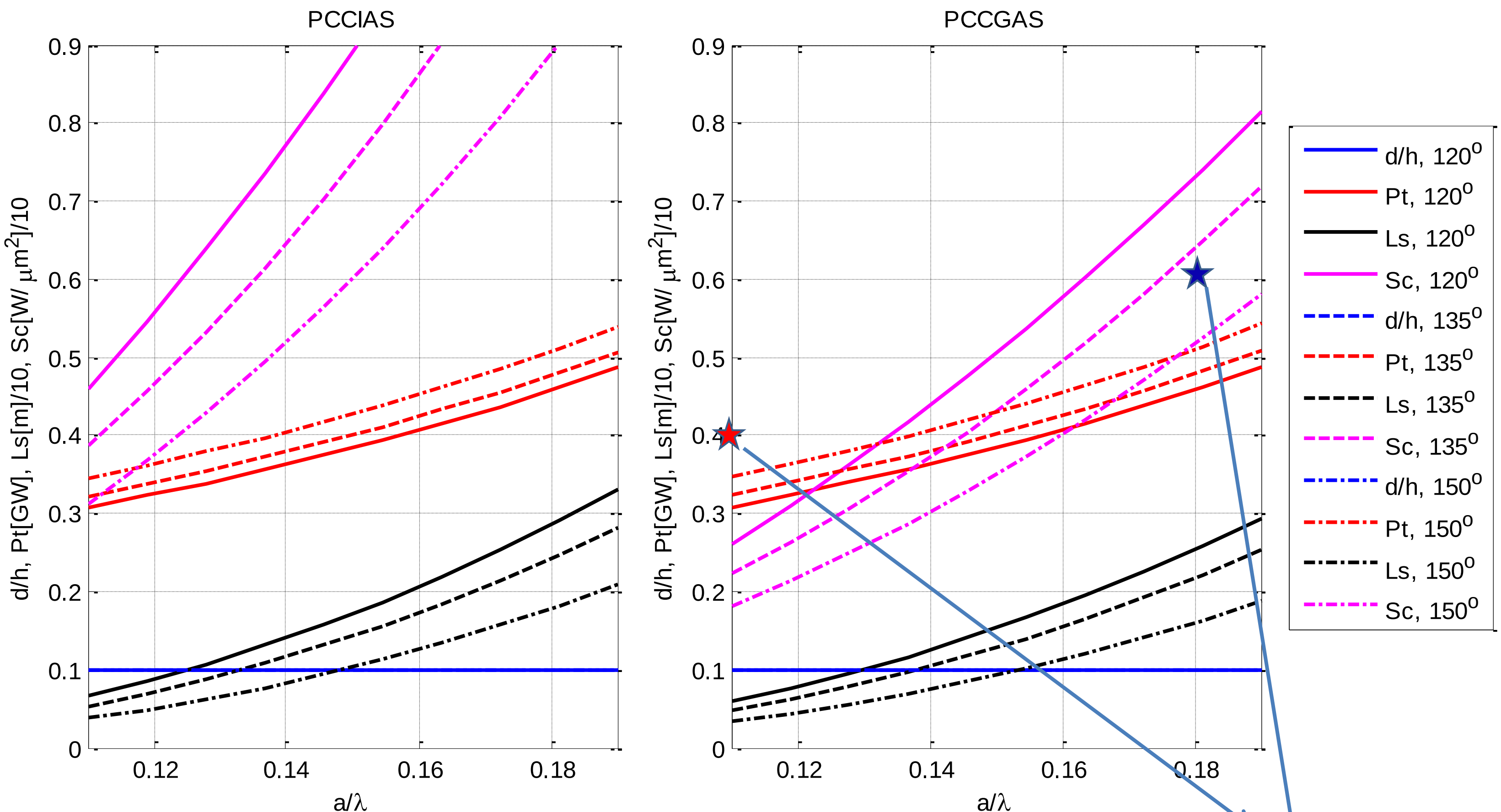
For high vg corner

Shorter tp
Higher vg_min

More Ptotal
Less Pin/klyst.

A little bit lower field and power quantities

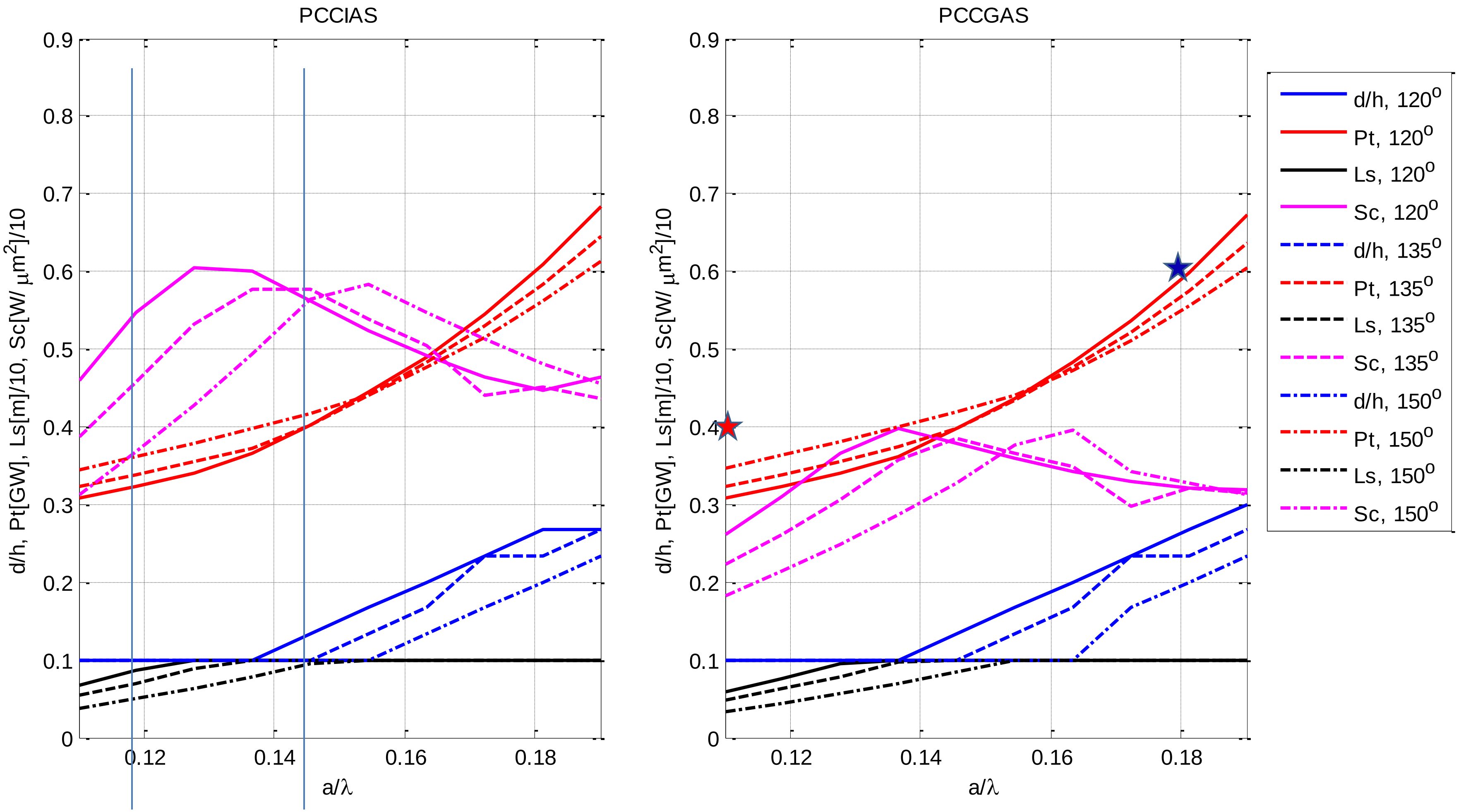
CIAS and CGAS with PC, different RF phase advance, no constraints



CLIC_G_undamped: τ_s=0.31 < τ_{s0}=0.54; Ls=0.25m; Qe=15700; Pt = 400MW

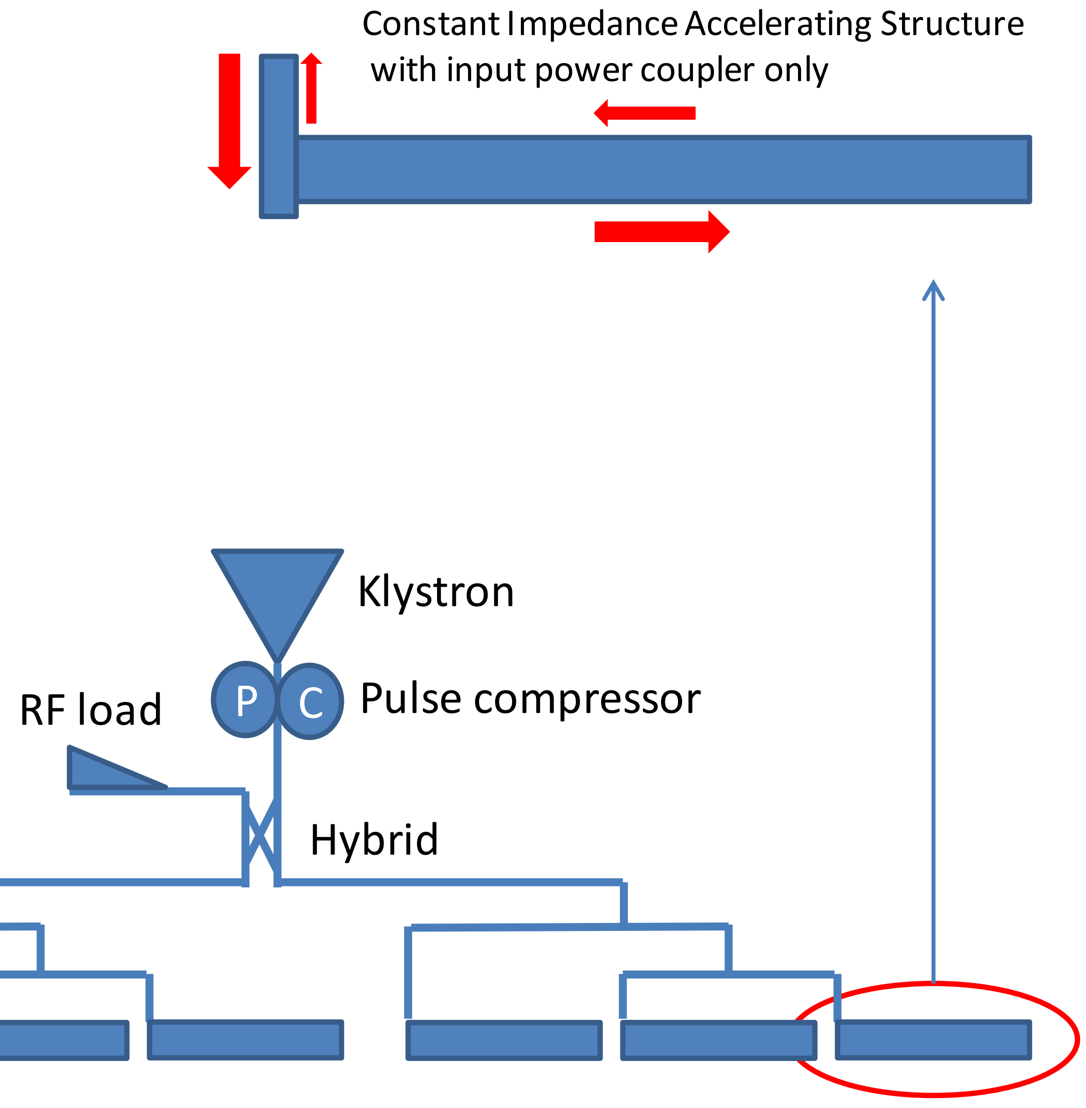
H75 : τ_s=0.50 ~ τ_{s0}=0.54; Ls=0.75m; Qe=20200; Pt = 613MW

CIAS and CGAS with PC, different RF phase advance, Ls < 1m



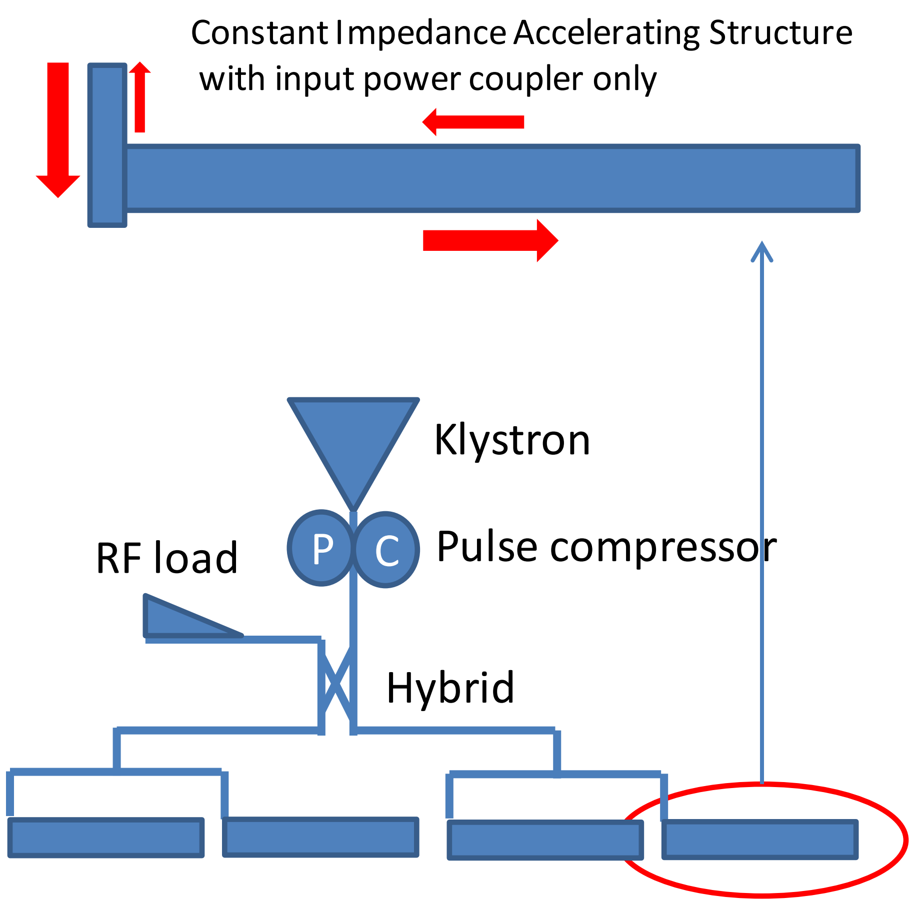
Small aperture linac, 2.4 GeV, 40m

RF phase advance	2π/3
a/lambda	0.118
d/h	0.1
Pt	322 MW
Ls	0.833 m
# klystrons	**8**
# structures	8 x 6 = 48
a	2.95 mm
d	0.833 mm
vg/c	2.22 %
tp	125 ns
Qe	20700



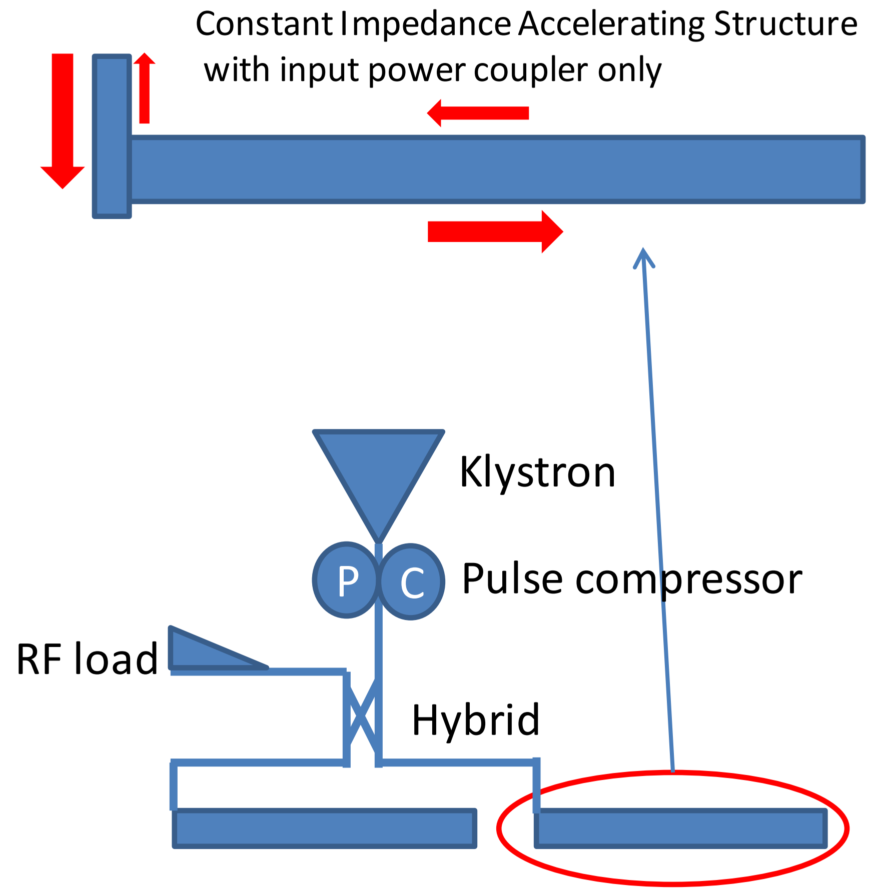
Middle aperture linac, 2.4 GeV, 40m

RF phase advance	2π/3	3π/4
a/lambda	0.145	0.145
d/h	0.1313	0.1
Pt	401 MW	401 MW
Ls	1 m	1 m
# klystrons	**10**	**10**
# structures	10 x 4 = 40	10 x 4 = 40
a	3.62 mm	3.62 mm
d	1.09 mm	0.937 mm
vg/c	3.75 %	3.29%
tp	90 ns	102 ns
Qe	18000	19000

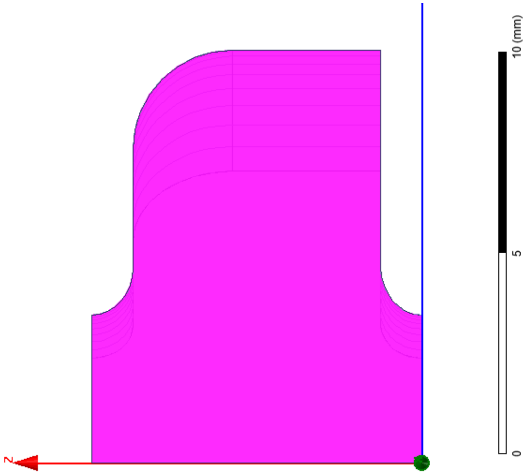


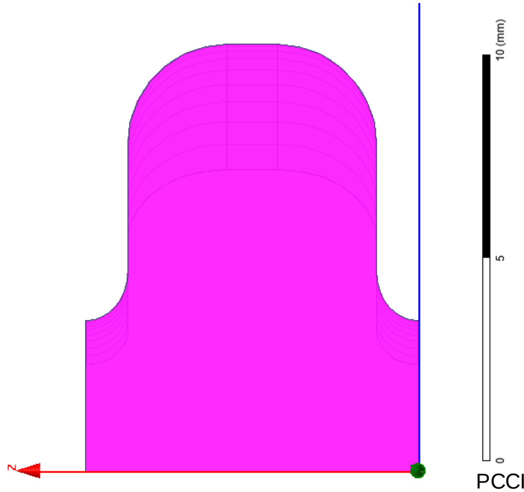
Large aperture linac, 2.4 GeV, 40m

RF phase advance	5π/6
a/lambda	0.195
d/h	0.183
Pt	602 MW
Ls	1.333 m
# klystrons	**15**
# structures	15 x 2 = 30
a	4.87 mm
d	1.90mm
vg/c	4.425 %
tp	101 ns
Qe	18500

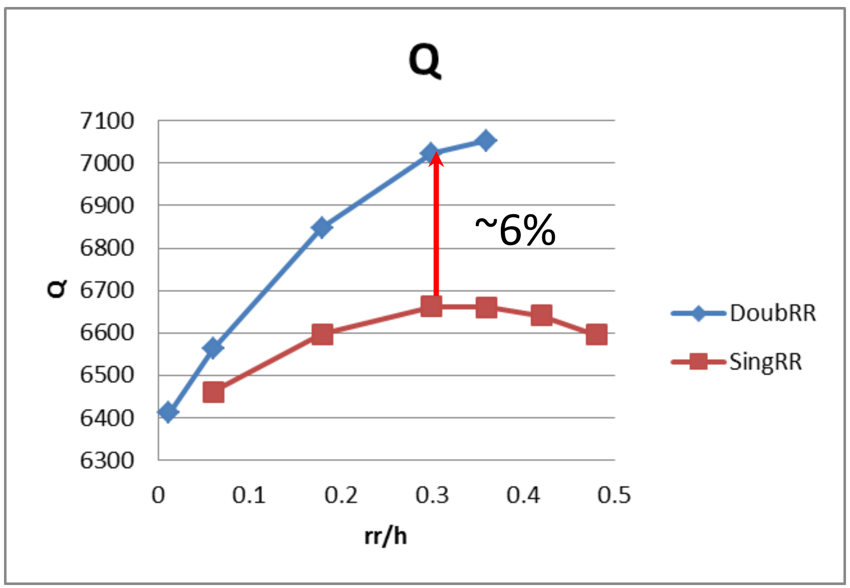


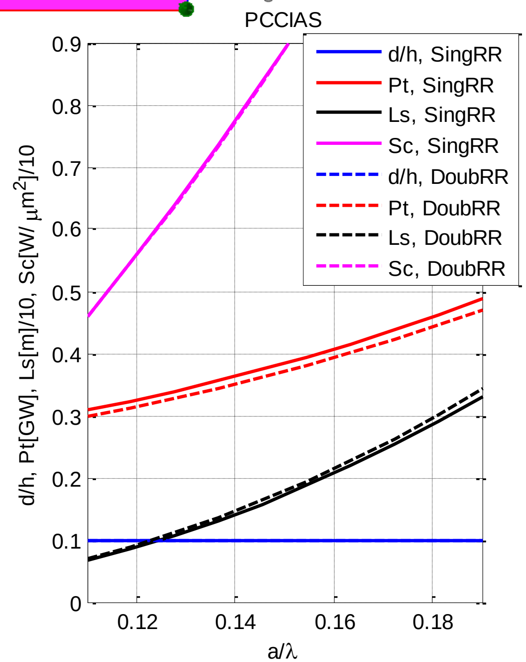
Single- versus Double-rounded cells

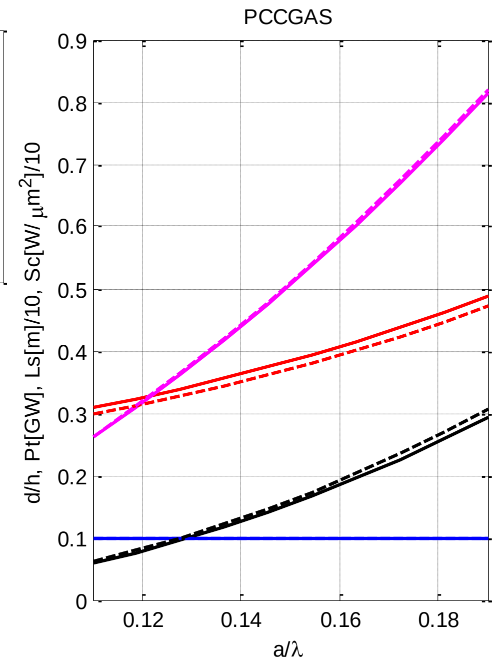




- By doing double rounded cells instead of single rounded cells Q-factor is increased by 6%
- The total linac power is reduced only by 3.7% (not 6%) because optimum is adapted to the Q
- No tuning will be possible







Conclusions

- An analytical expression for effective shunt impedance of the CI and CG AS without and with pulse compression have been derived.
- Maximizing effective shunt impedance for a given average aperture gives the optimum AS+PC design of a single bunch linac
- Different constraints have been applied to find practical solutions for a FERMI energy upgrade based on the X-band 2.4 GeV, 60 MV/m linac