Optimisation of single bunch linacs for possible FEL upgrades

Alexej Grudiev, CERN

6/02/2014

CLIC14 workshop

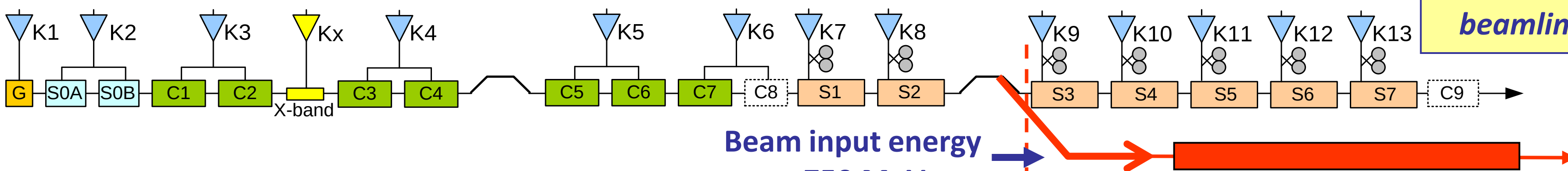
Linac layout and energy ugrading

Motivation from Gerardo D'Auria CLIC13

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 λ < 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:

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

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

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

$$W_\perp^{'}(\sigma_z) = \left.\frac{dW_\perp^{'}(s)}{ds}\right|_{s=0} \sigma_z = \frac{4Z_0 c}{\pi a^4}\sigma_z$$

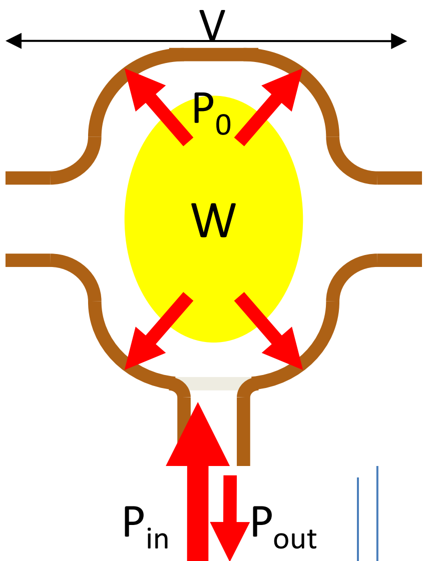
$$E(z) = E_0 + eGz;$$

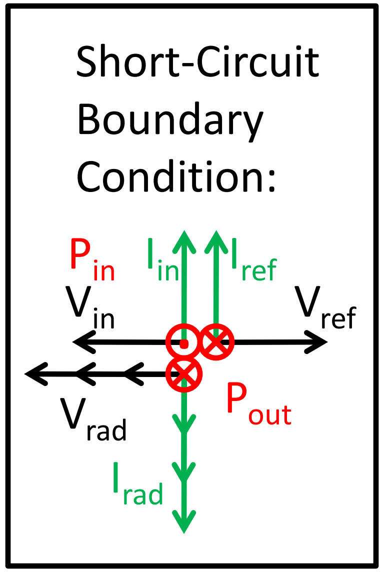
$$\gamma = \frac{Z_0 c}{\pi} \frac{eN\sigma_z}{\langle\beta\rangle a^4 G} \ln\left(\frac{E_L}{E_0}\right)$$

	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





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

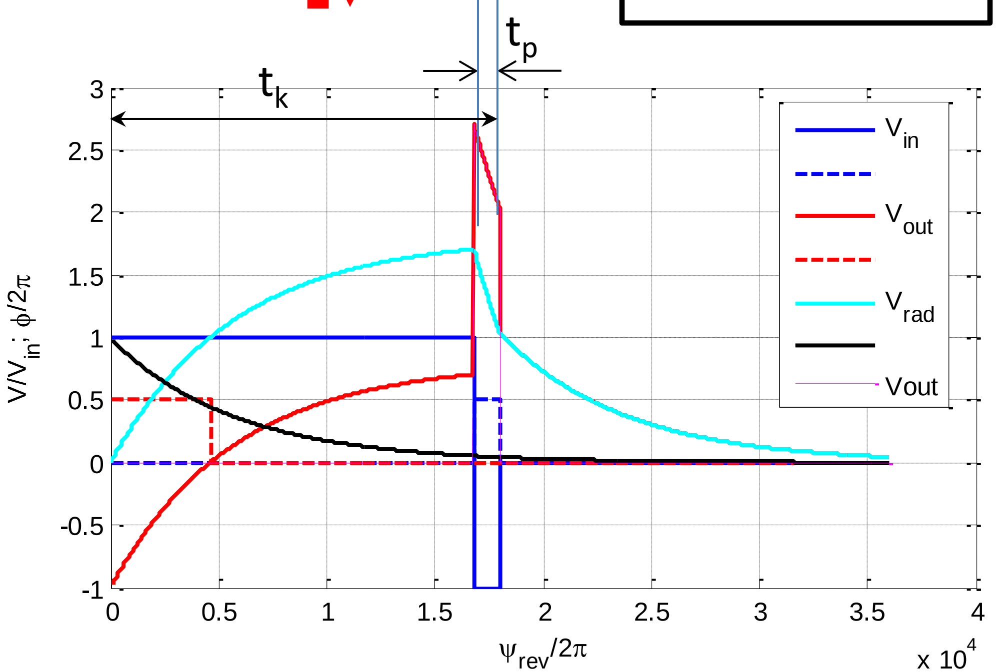
$$V_{out} = V_{rad} + V_{ref} = V_{rad} - V_{in}$$

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

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

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

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



Analytical expression for the pulse shape

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

Effective shunt impedance of Acc. Structure + Pulse Compressor

Effective shunt impedance of TWAS ** + Acceleration in TWAS for transient pulse shape from PC * = Effective shunt impedance of TWAS+PC **

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

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

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

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

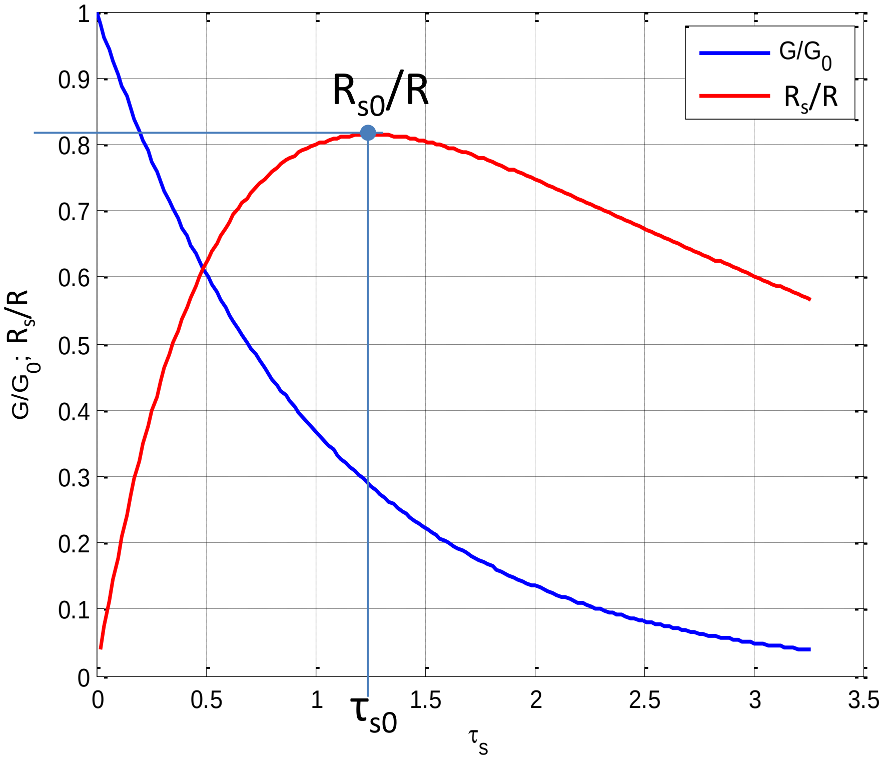
Effective shunt impedance: $R_s = \frac{V_a^2}{P_{in} L_s} [\Omega / m]; \quad P_{tot} = \frac{V_{tot} \langle G \rangle}{R_s}$

* 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)

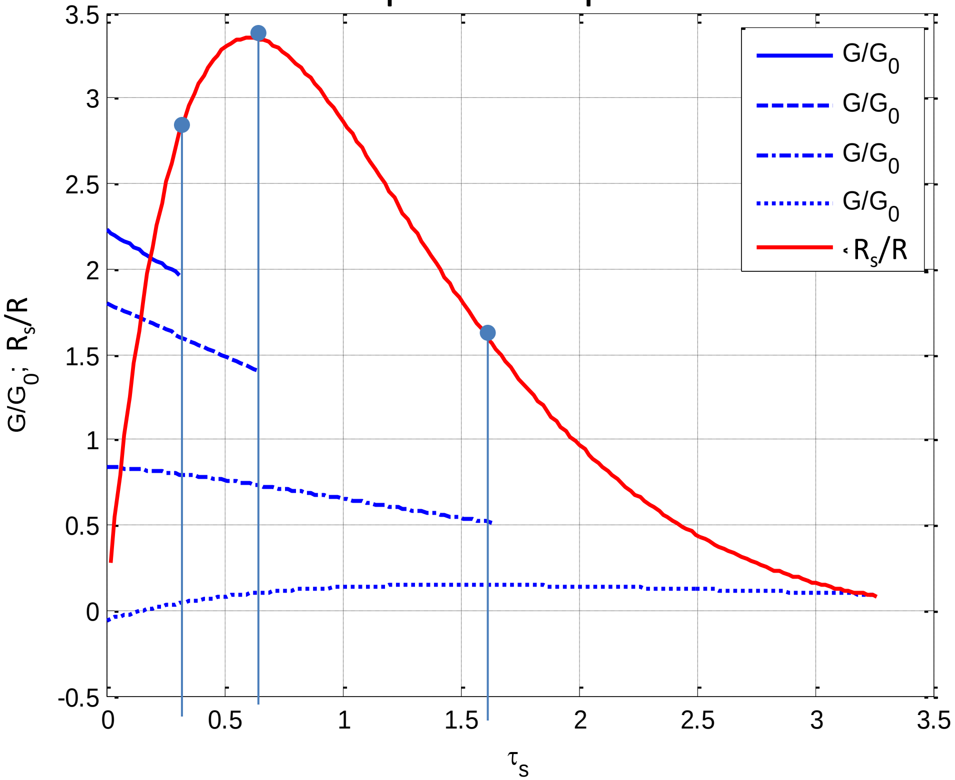
Effective Shunt impedance in Const Impedance (CI) AS

No pulse compression



τ_{s0} = 1.2564 => R_{s0}/R = 0.8145

With pulse compression

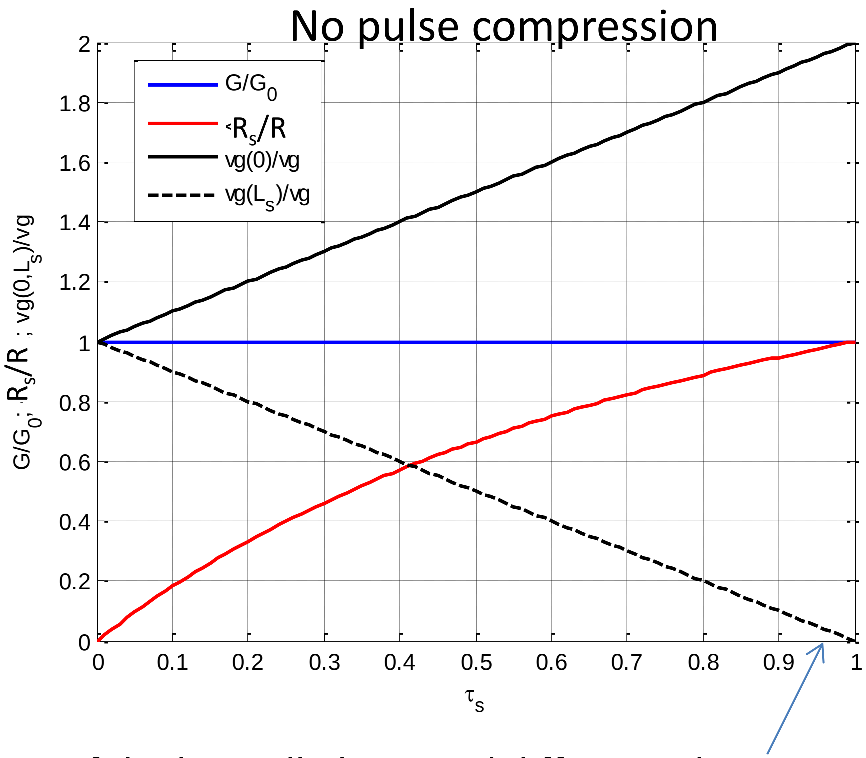


For Q = 8128; Q_0 = 180000; Q_e = 20000

τ_{s0} = 0.6078 => R_{s0}/R = 3.3538

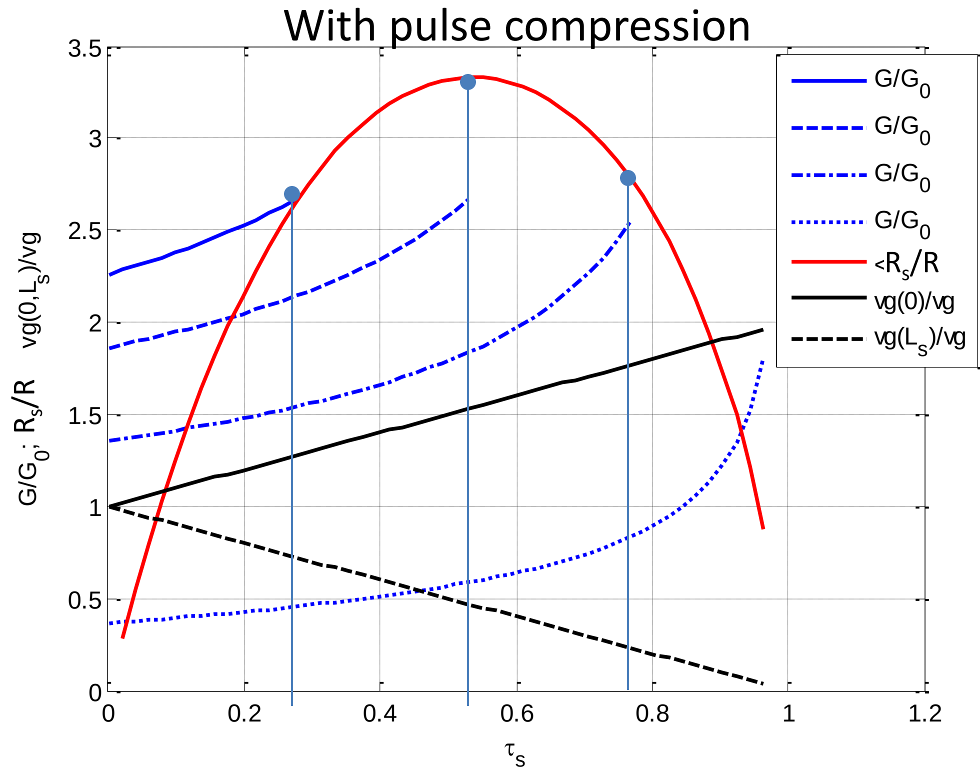
But in general it is function all 3 Qs: Q, Q_0, Q_e

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

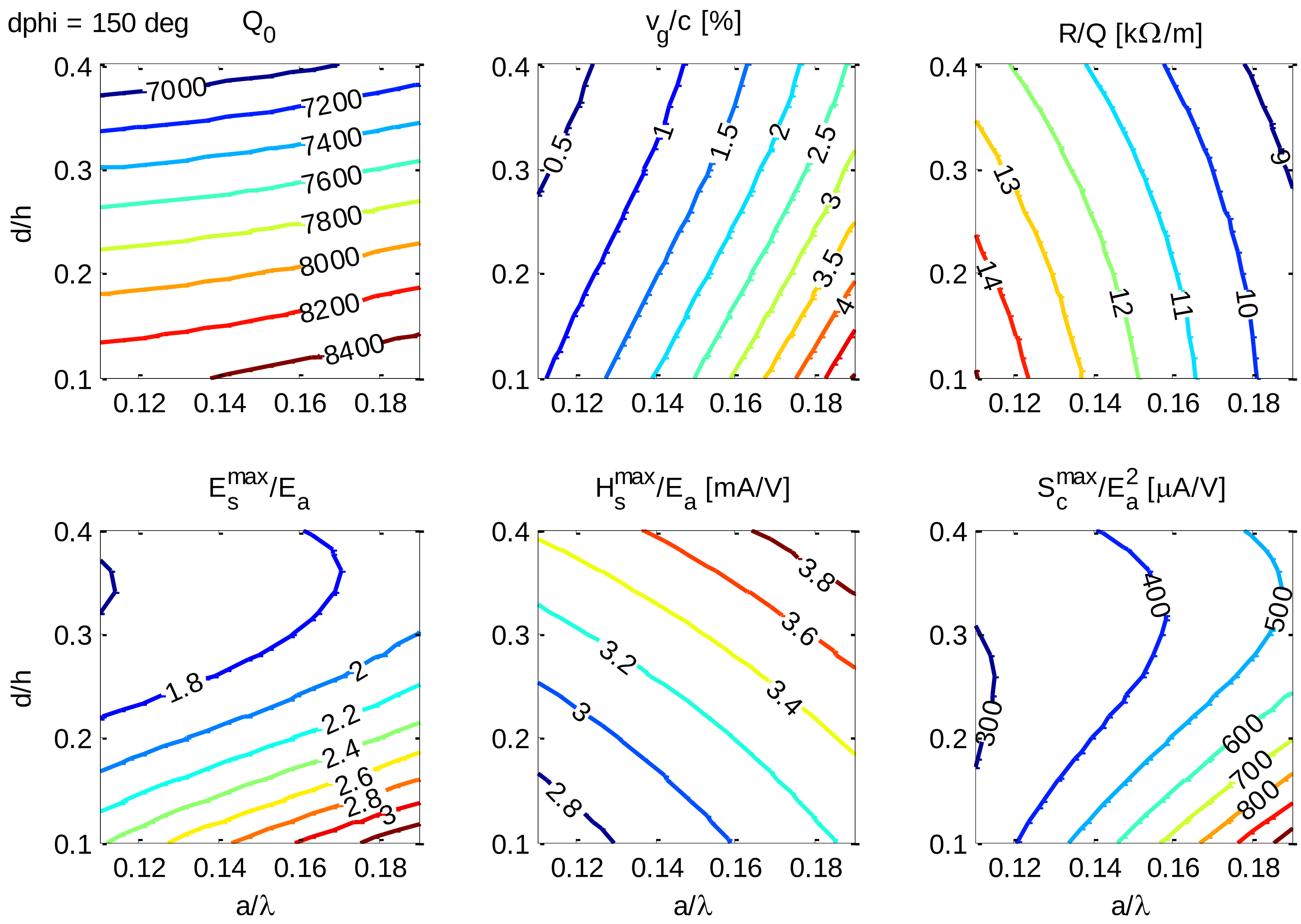
Lowest group velocity limits the CGAS performance



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

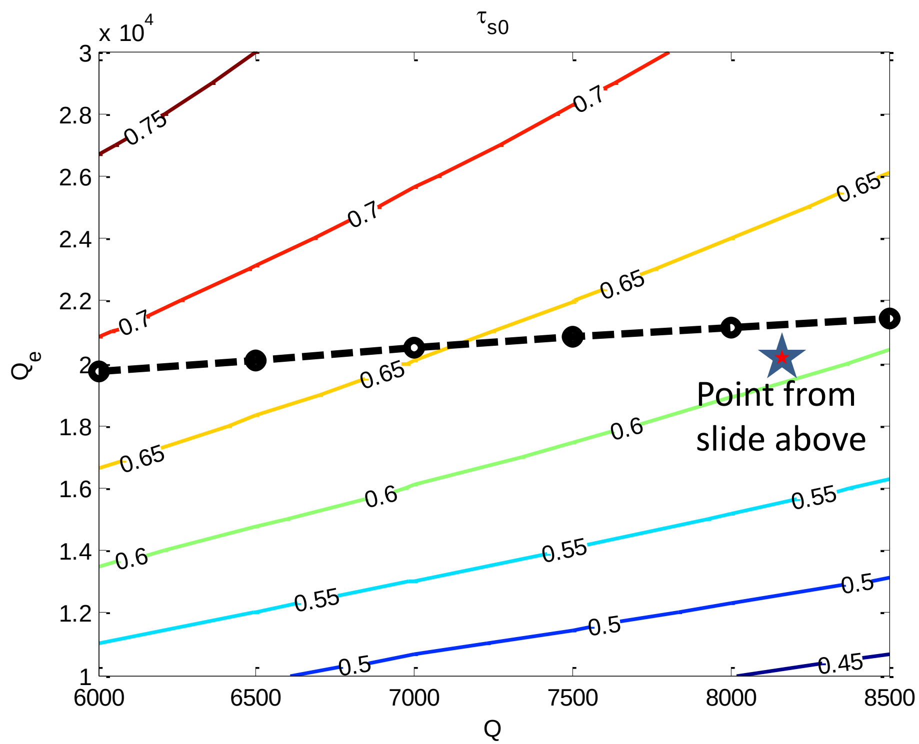
Undamped cell parameters for dphi=150°



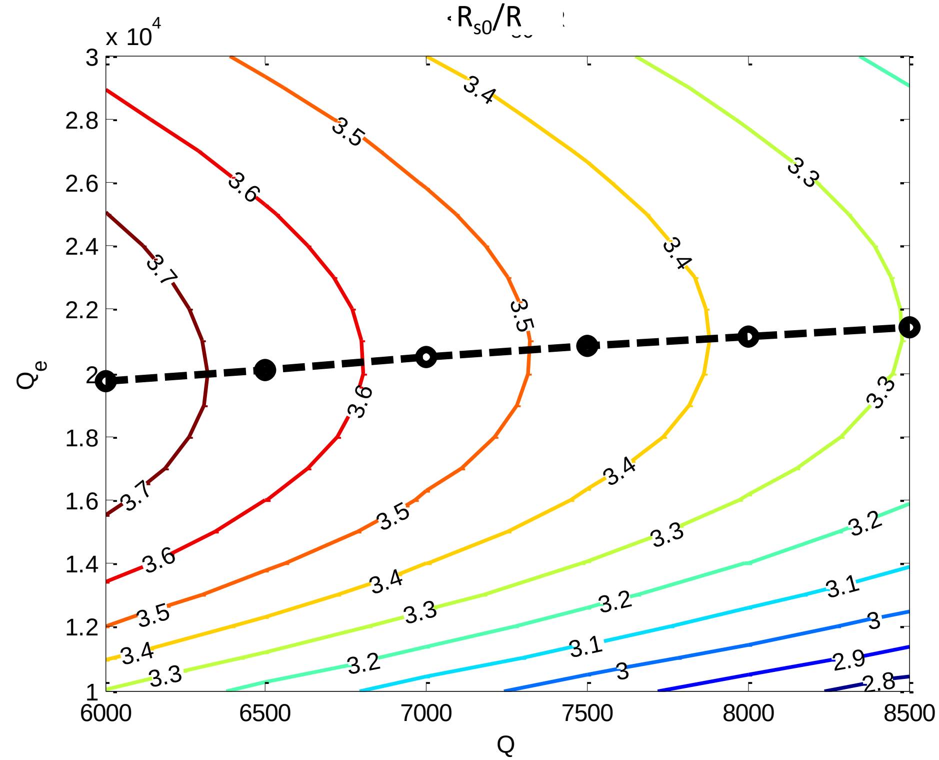
CIAS pulse compression optimum

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

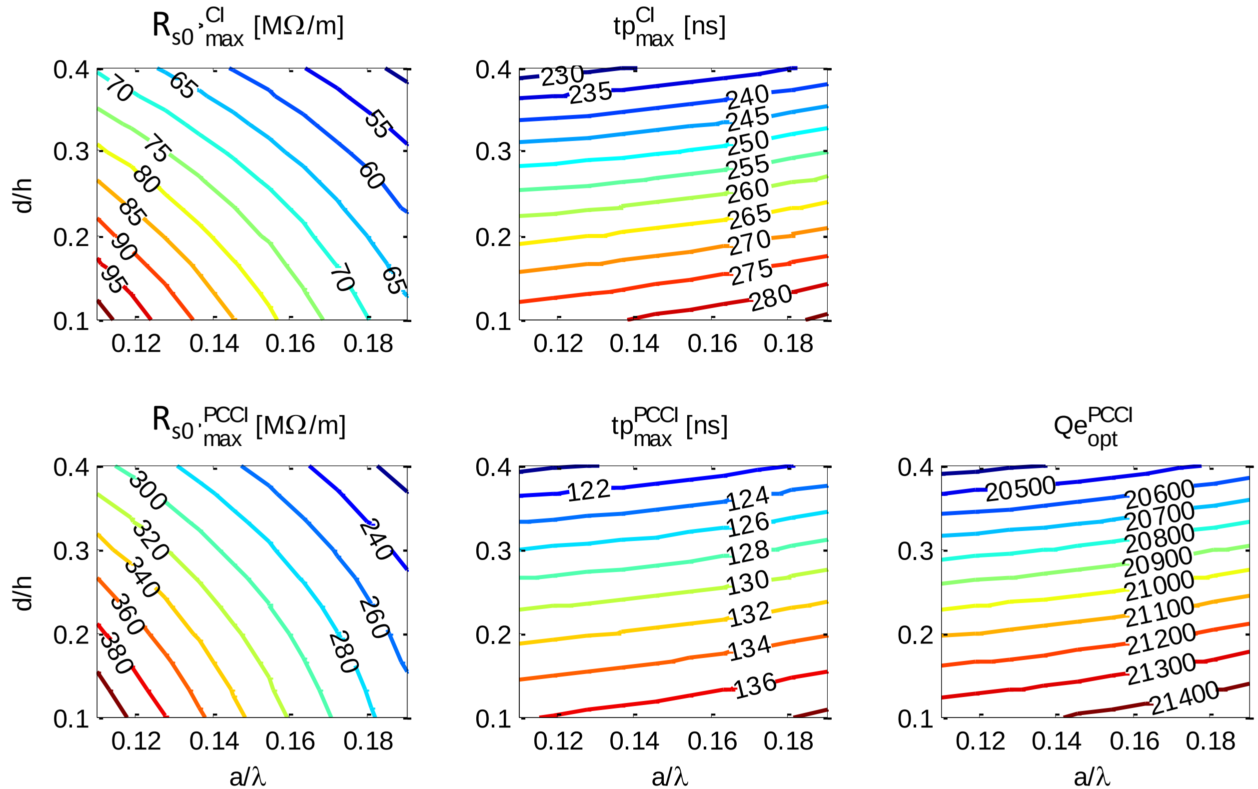


Optimum value of Q_e ~ const: ranges from 20000 for Q=6000 up to 21000 for Q=8000

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

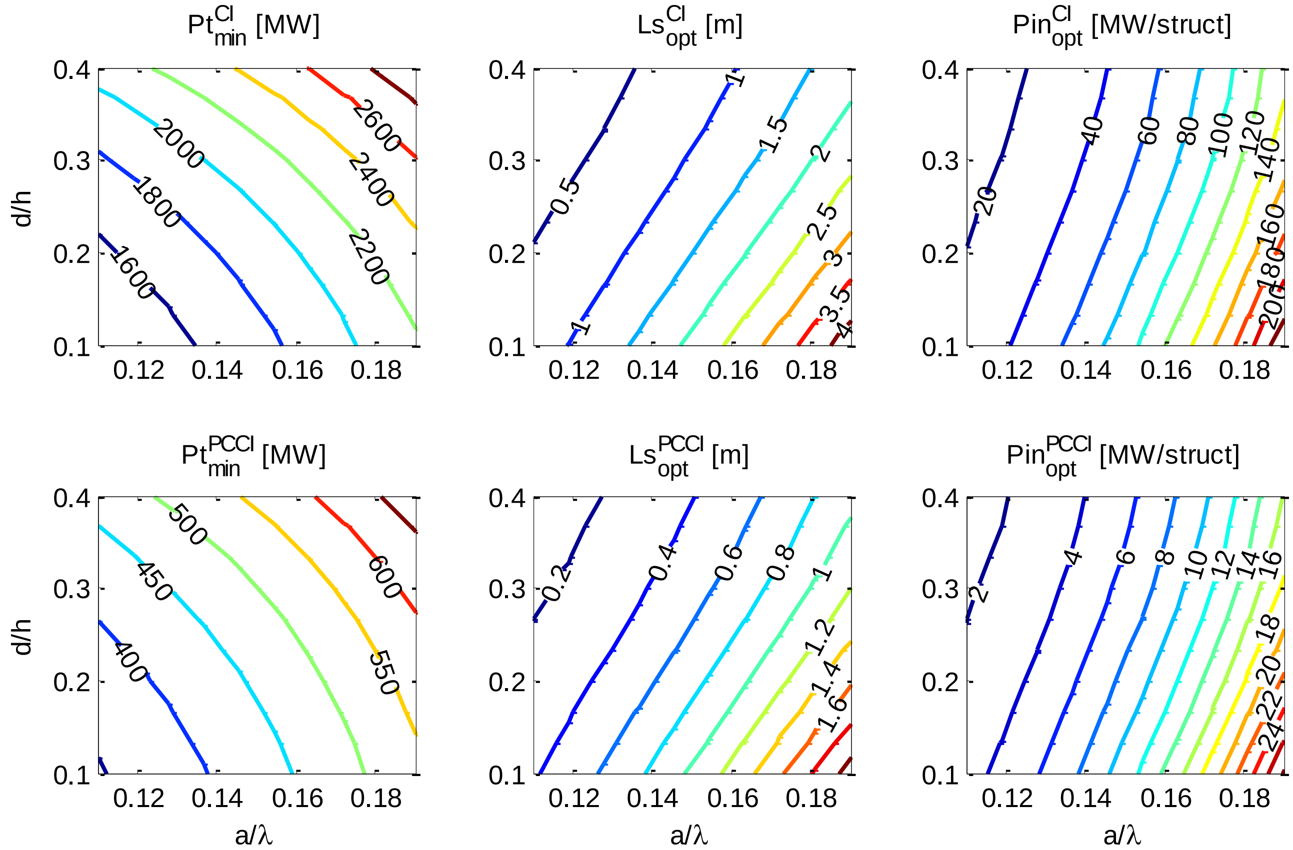
CIAS linac 40 m long, <G>=60MV/m : w/o and with PC

Total klystron power

Optimum structure length

Klystron power per structure

~# of structures per 0.8x50 MW klystron

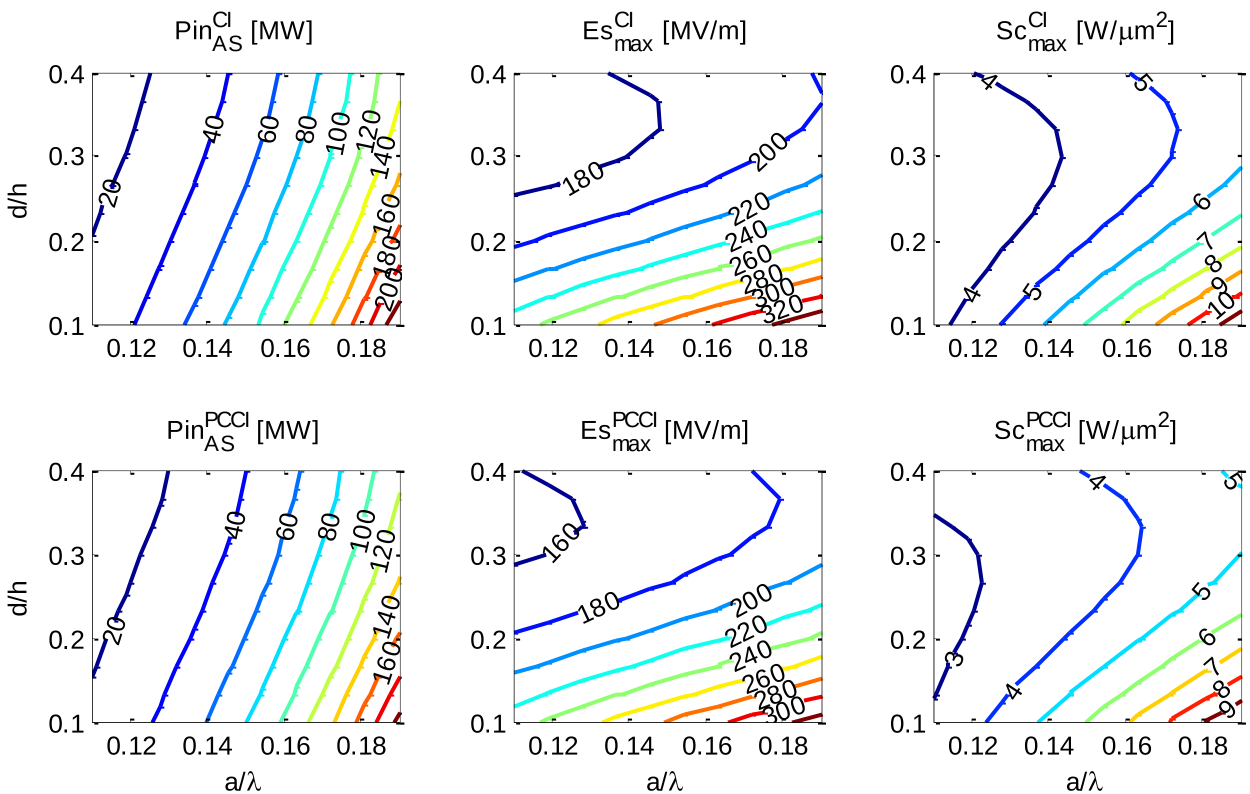


2 -> 1/5

~20 -> ~2

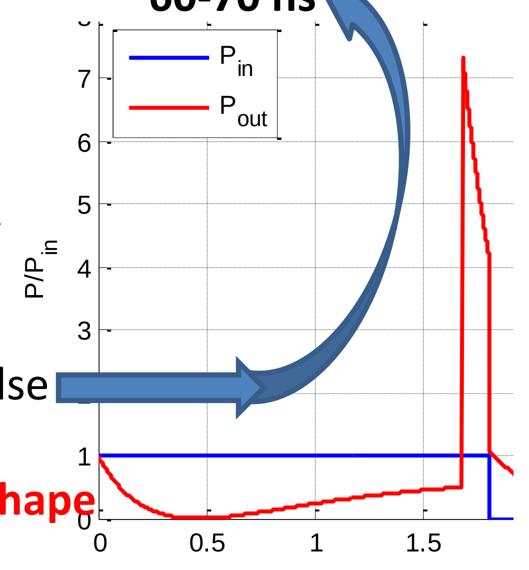
CIAS high gradient related parameters: w/o and with PC

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



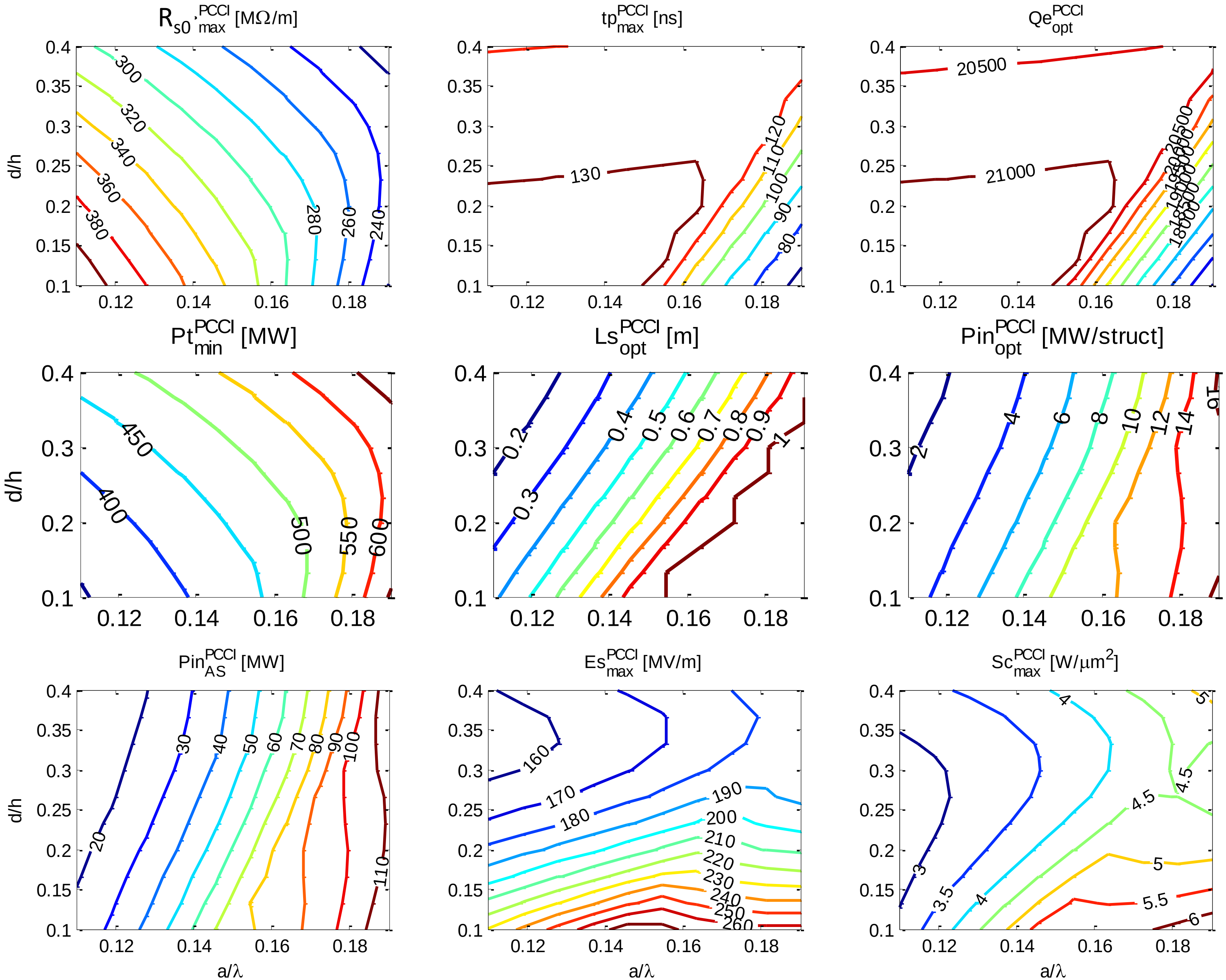
Assamption:

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

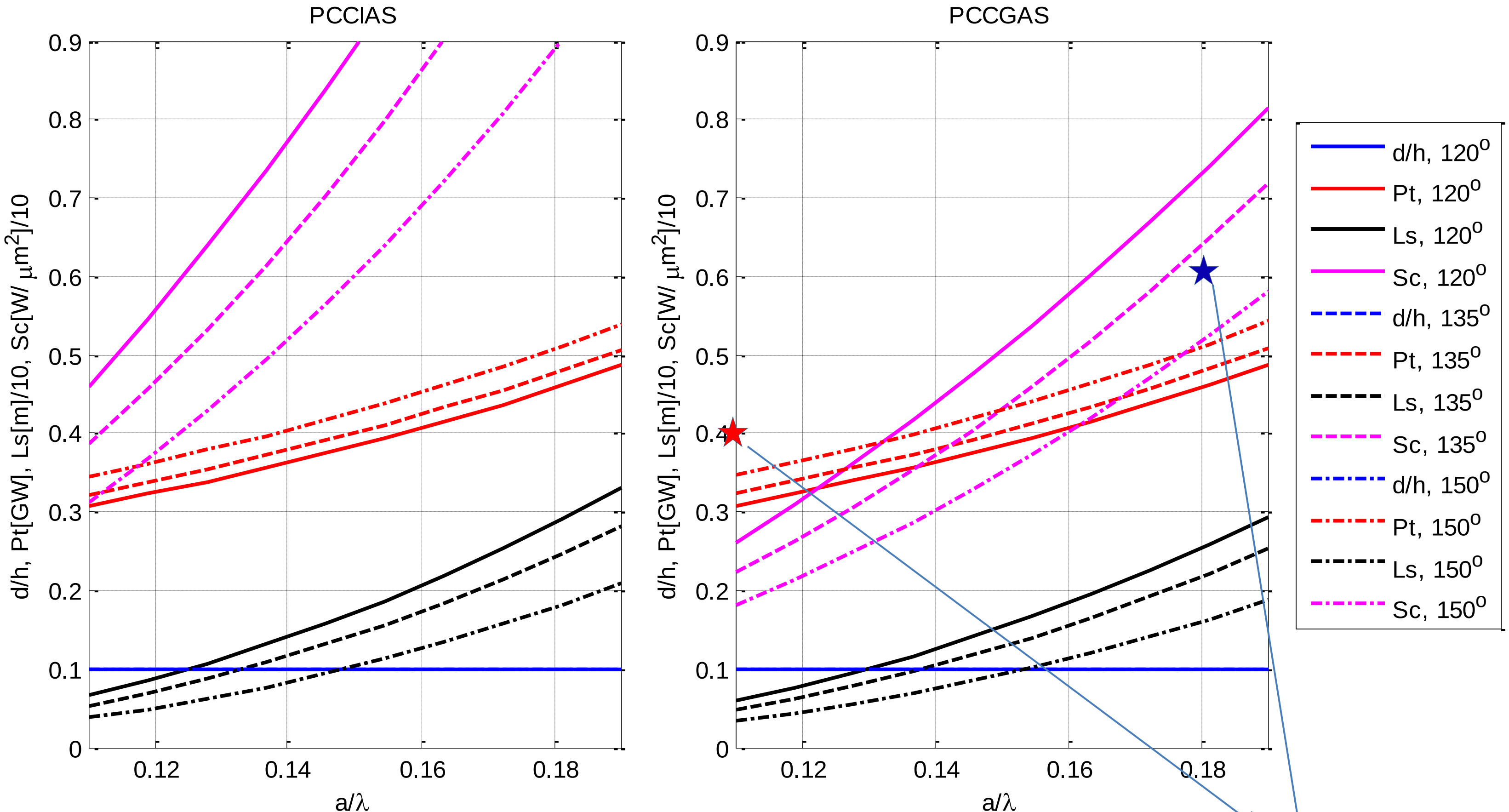


For high vg corner
Shorter tp
Lower Qe

More Ptotal
Less Pin/klyst.

Lower field and power quantities

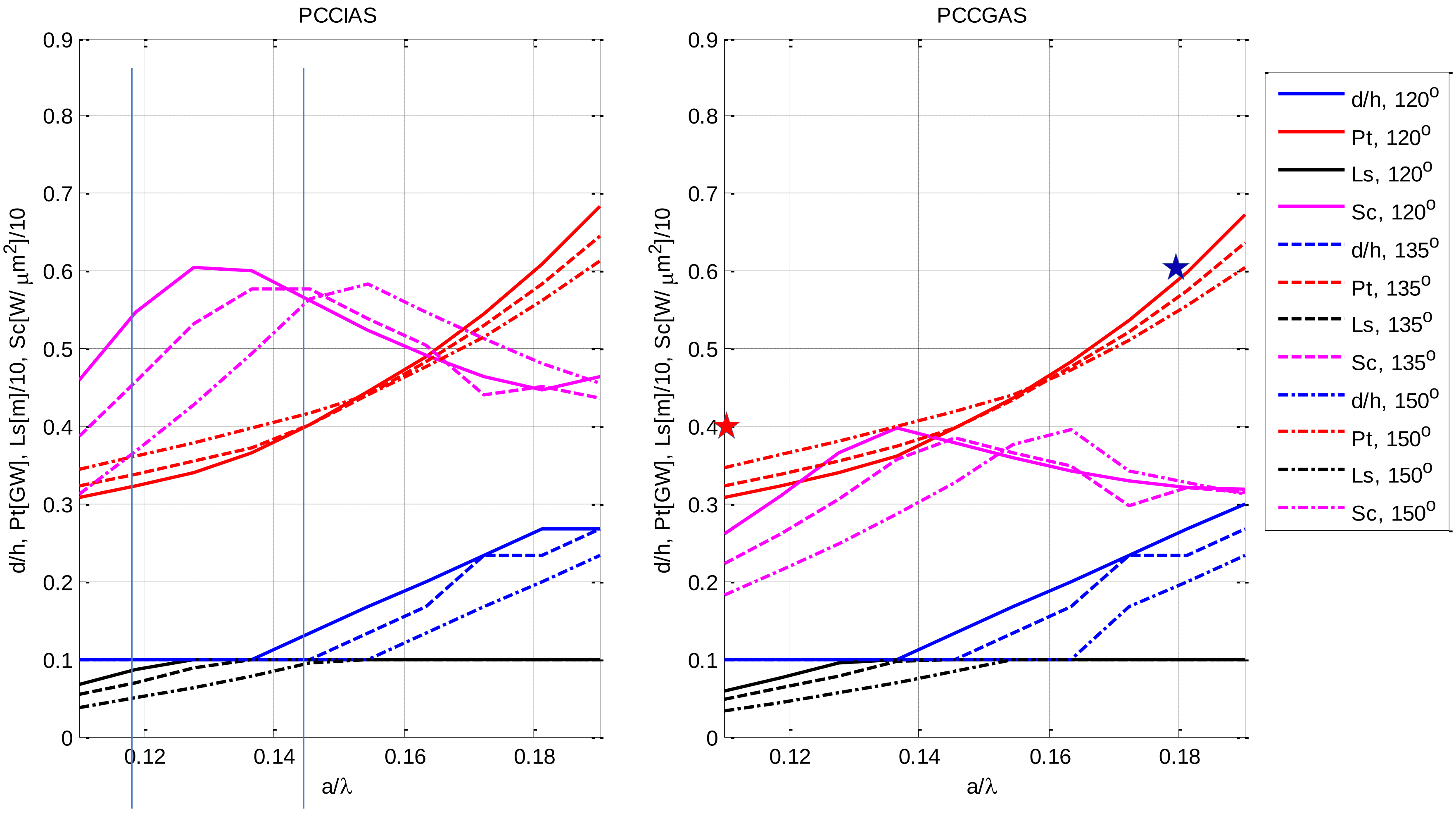
CIAS and CGAS with PC, different RF phase advance, no constraints



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

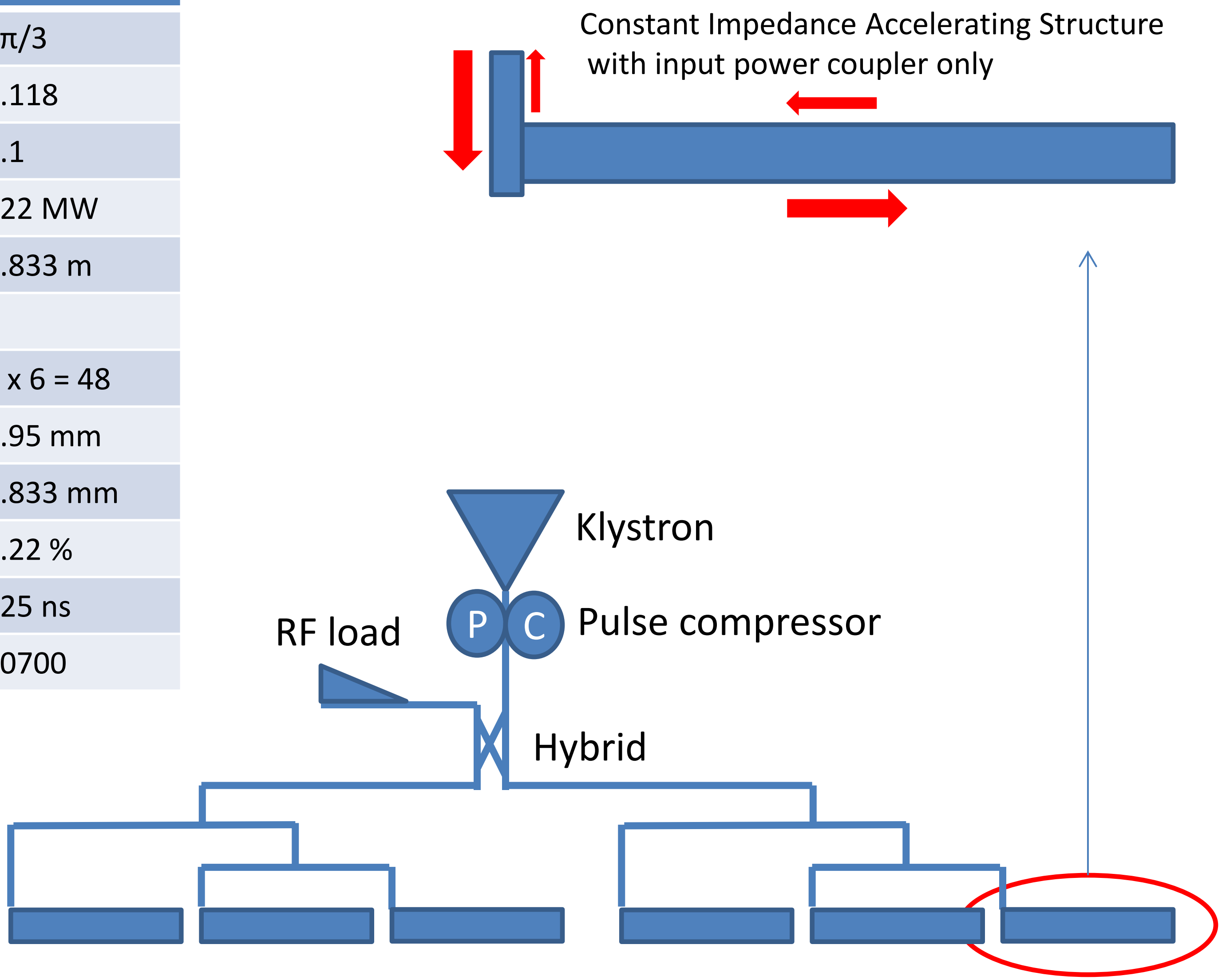
H75 : τ_s=0.50 ~ τ_{s0}=0.54; Ls=0.75m; Qe=20200; Pt = 613MW

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



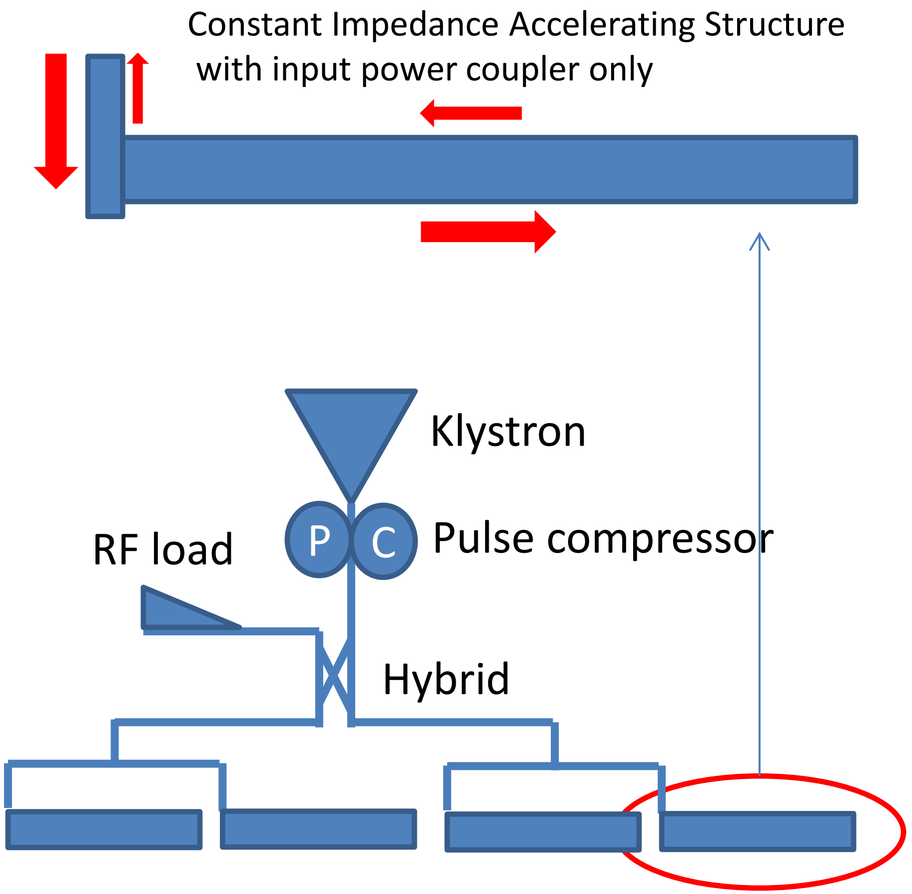
Small aperture linac, 2.4 GeV, 40m

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



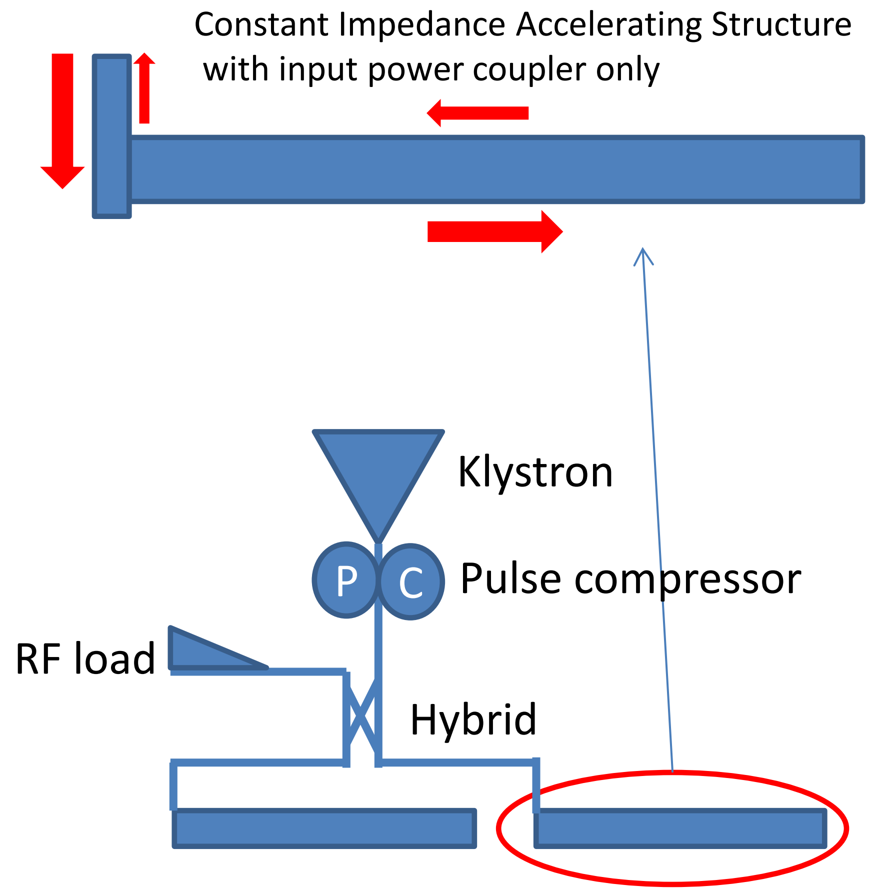
Middle aperture linac, 2.4 GeV, 40m

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



FERMI energy upgrade

- 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
- Closer look together with beam dynamics experts is necessary to chose the right structure

Motivations from PSI

PAUL SCHERRER INSTITUT

X-band applications in SwissFEL, ATHOS line

ATHOS energy vernier

Motivation
Independent beam energy control in both FELs

Situation
Space for 2 RF stations,
4 linac girders of 4 m each
± 400 MEV required

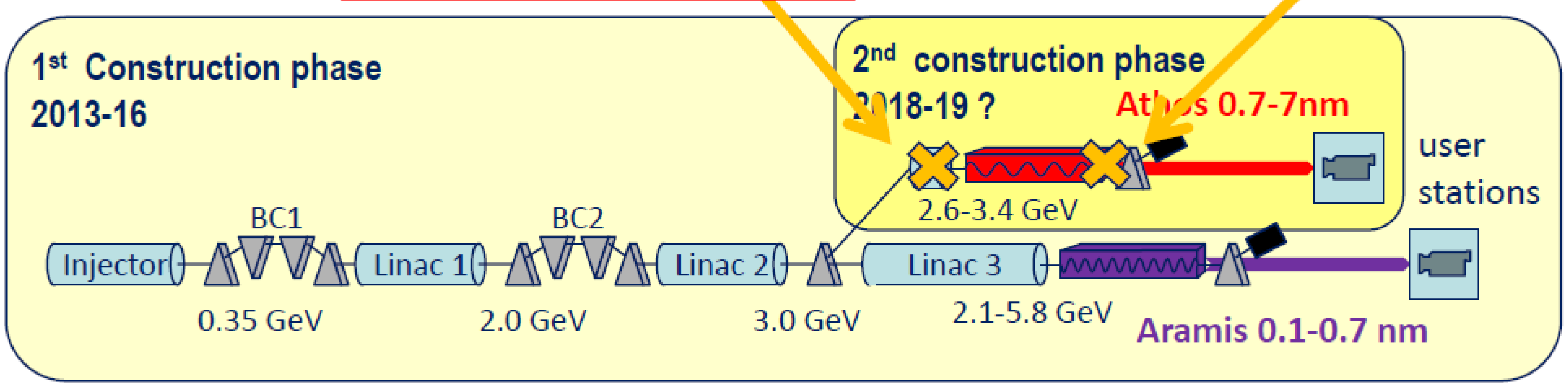
Timescale
2017-2020

ARAMIS post undulator RF Deflector

Motivation
Continous long. Phase space monitoring incl. FEL dynamcis

Situation
Space for 1 RF stations,
1 linac girders of 4 m each

Timescale
>2019



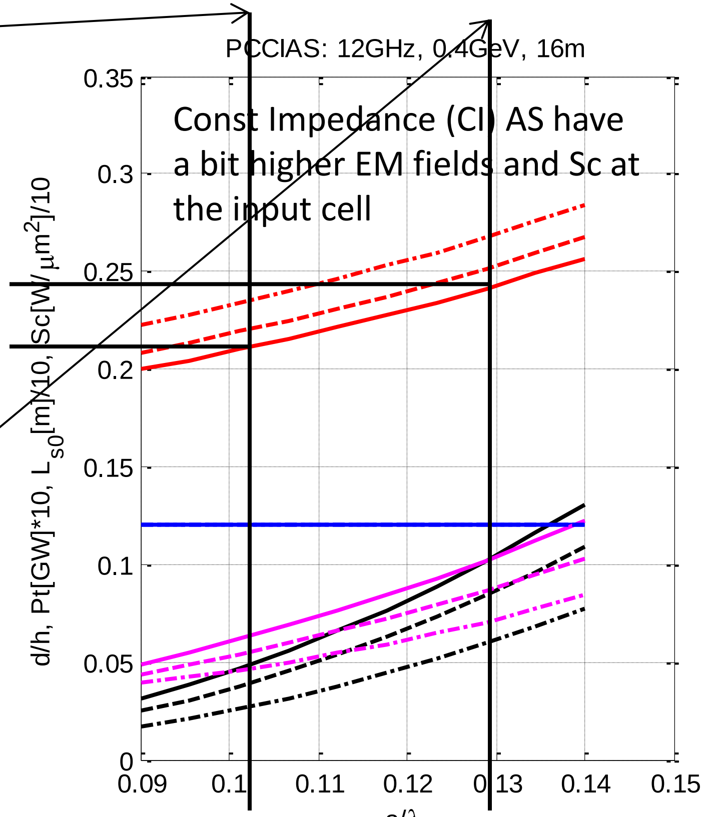
X-band Energy Vernier for ATHOS

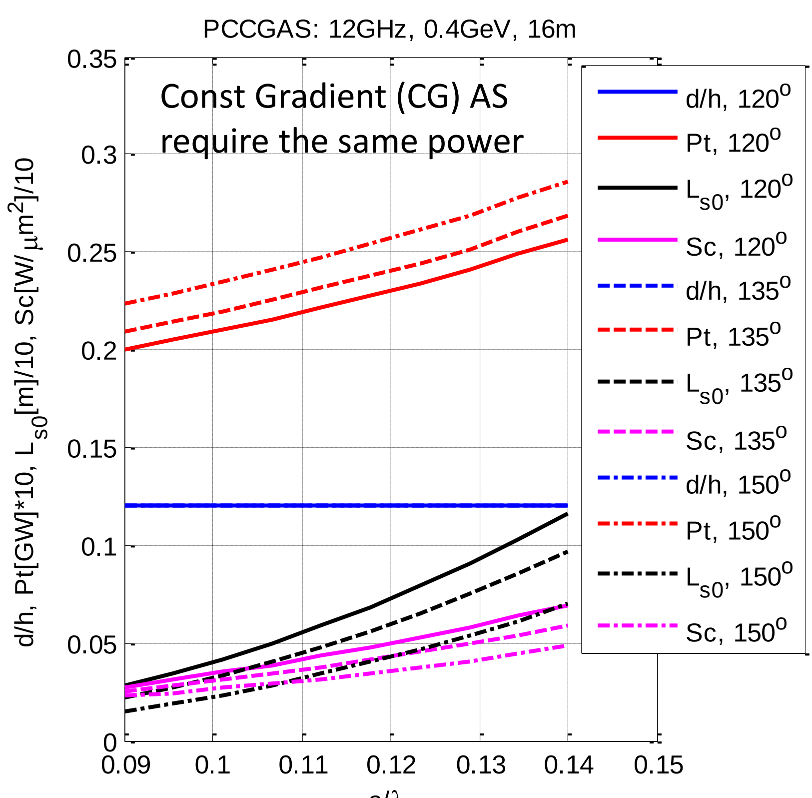
Parameters specs:
Required energy gain: dE = +-0.4 GeV
Total length available for acceleration: Lt = 16 m
If: the aim to introduce the **same** amount of Longitudinal Wake (W_L) as in C-band Linac3: W_L3
Then: Since W_L~L/a^2: <a_X> = <a_C>/sqrt(L3_C/Lt)=6.44mm/sqrt(104m/16m)=2.53mm => <a_X>/λ=0.101

Total power from the klystrons at 1.5us: Ptot is significantly less then on can get from one XL5 and we are far from breakdown limit. => higher dE is possible even with one XL5.
For example, for 0.5 m long CIAS: 40MW => 0.53GeV or 2x40MW => 0.76GeV

a/λ=0.102
98% of W_L3
L_s = 0.5m
32 CI Acc. Str.
Ptot = 22MW
+ WG loss +
op. margin

a/λ=0.129
61% of W_L3
L_s = 1m
16 CI Acc. Str.
Ptot = 24MW
+ WG loss +
op. margin

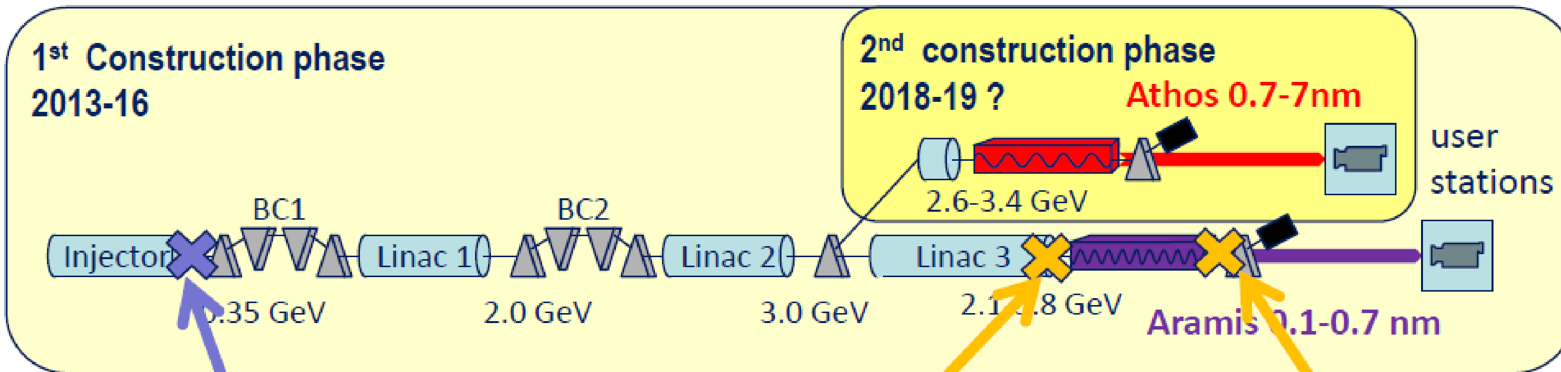




More motivations from PSI

PAUL SCHERRER INSTITUT PSI

X-band applications in SwissFEL, ARAMIS line



X band lineariser

Motivation
Essential for long. phase space control

Situation
1 XL5
2 structures

Timescale
Exists, <u>but situation for spares critical</u>

ARAMIS energy upgrade

Motivation
Increase Photon energy range
Increase FEL power

Situation
Space for 3 RF stations,
6 linac girders of 4 m each

Timescale
>2020

ARAMIS post undulator RF Deflector

Motivation
Continous long. Phase space montioring incl. FEL dynamcis

Situation
Space for 1 RF stations,
1 linac girders of 4

Timescale
>2017

ARAMIS energy upgrade.

- It is probably unreasonable to take 0.5 m CIAS from the previous slide since it is too short and aperture is too small (there is already enough W_L in ARAMIS line)
- Taking 1m long CIAS from the previous slide: 24m long X-linac with 3 XL5s (3x40MW) can provide energy increase: dE = **1.1GeV**. In this case, we may come close to the BDR limit of 4MW/mm^2 (BDR~1e-7) so we may start to see some breakdowns at this levels !
- The above 1m long CIAS is rather close to a potential Fermi linac energy upgrade structure (middle aperture). It probably can be the same structure for both projects.
- A different structure (i.e. larger aperture) is maybe a better choice. More refined specs are needed to make optimized design.