The PIMS structure

1st Linac4 Review Committee

MAC'08, January 29th - 30th, 200

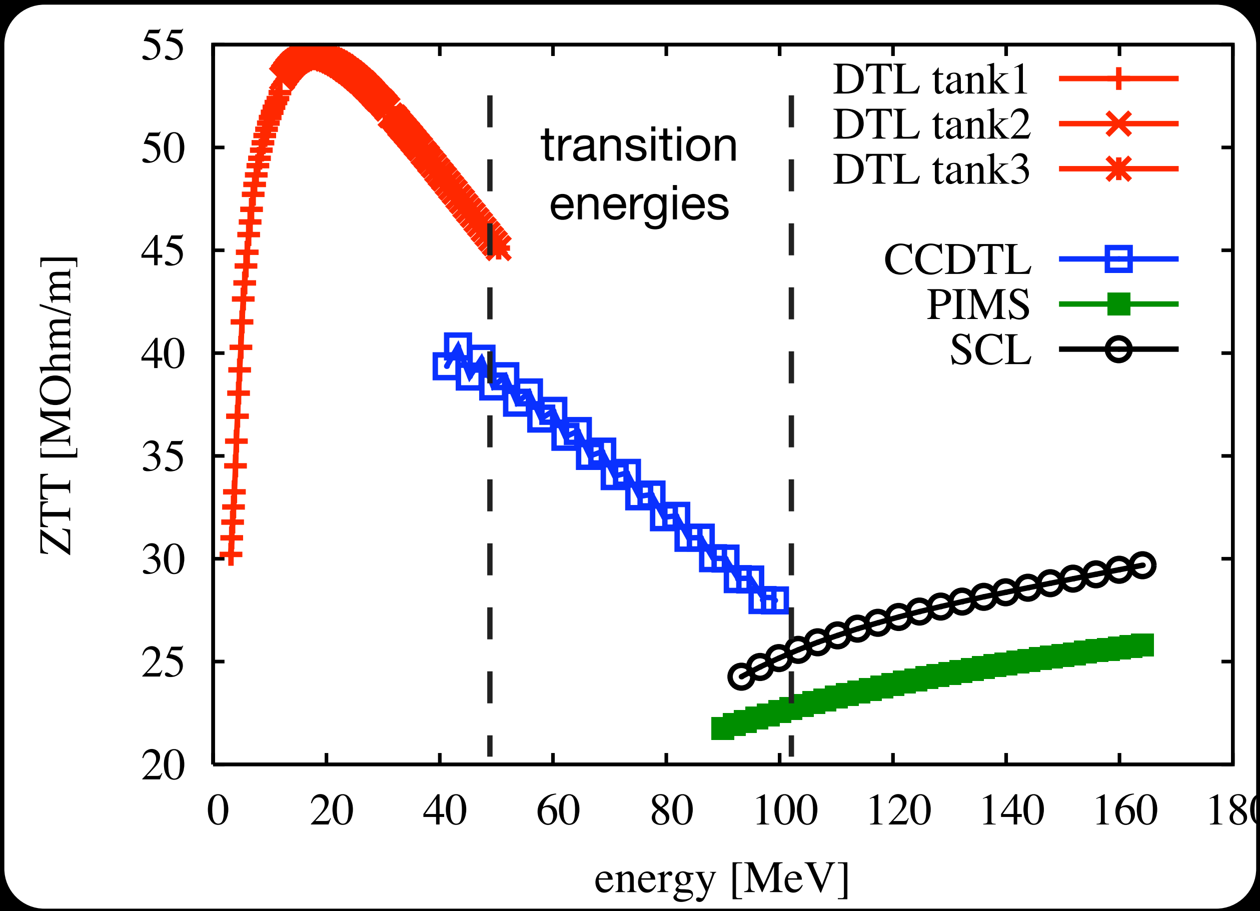
CERN, Geneva, Switzerland

Frank Gerigk, Rolf Wegner

Outline

- Motivation to replace the SCL with a PIMS,
- voltage errors, coupling errors, tolerances,
- tuning, transient beam loading,
- construction issues.

between 90 and 160 MeV...



90 to 160 MeV

SCL: 4 modules of 5 x 11-acc.-cell cavities, 704.4 MHz,

or

CCDTL: 5 3-acc.-cell cavities, 352.2 MHz

PIMS:102-160 MeV 12 x 7-cell cavities, 352.2 MHz

ZT^2 (80%), including losses due to stems, end walls, coupling holes, tuning rings...

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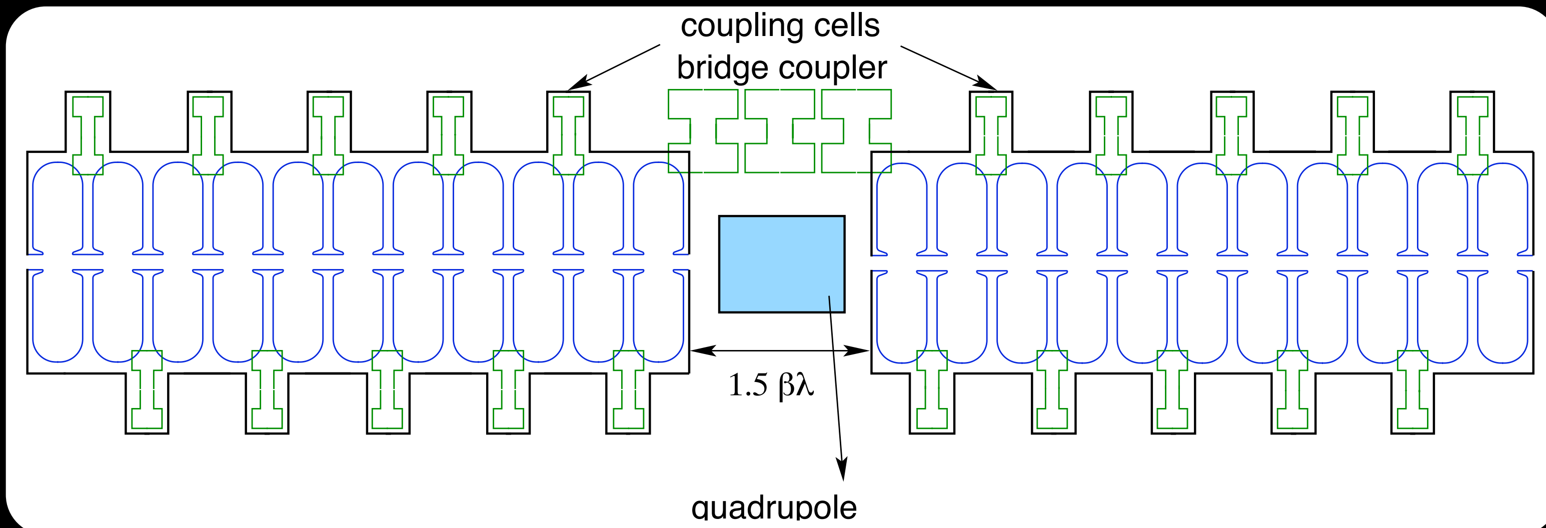
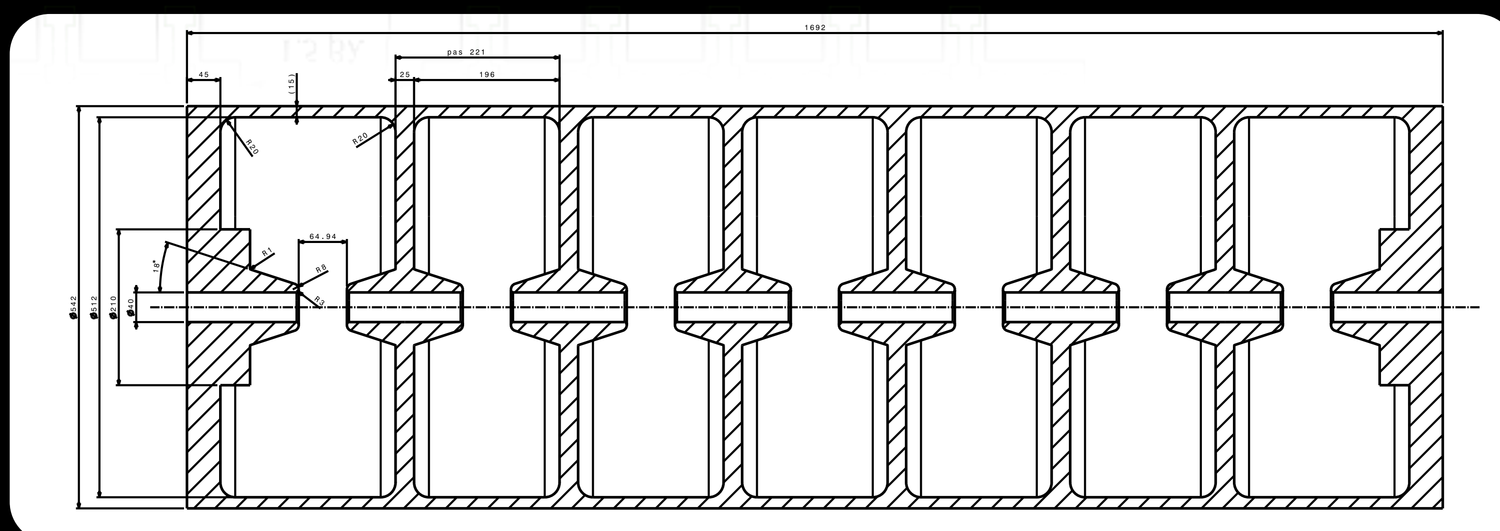
SCL versus PIMS I



coupled 11-cell pi/2-mode cavity, 704 MHz

SCL
old solution



PIMS
new solution

7-cell pi-mode cavity, 352 MHz

SCL versus PIMS II

SCL	PIMS (+CCDTL)
higher ZT^2, P_{peak}=12.5 MW,	lower ZT^2, P_{peak}=13.6 MW,
length: 28 m,	length: 27.8 m,
4 modules with 5 coupled cavities, 468 cells, π/2 mode,	5 CCDTL cavities + 12 7-cell PIMS cavities, 103 cells, π mode,
high construction & tuning effort,	simplified construction & tuning,
704.4 MHz (2 frequencies),	352.2 MHz (single frequency),
cost (cavities + RF system): 5.2+6.2 = 11.4 MCHF + energy ramping	cost (cavities + RF system): 4+6.9 = 10.9 MCHF
non-trivial cooling,	no risk of water/vacuum breach,
one module per klystron (117 cells),	two cavities per klystron (14 cells),
similar beam dyn. performance, for PIMS: energy ramping with last 2 cav.	

SCL versus PIMS: frequency

- one single frequency: simplified RF distribution and low-level control system, common RF coupler design for all structures (iris-coupling from a tangential $\lambda/4$ short-circuited wave-guide),
- now we start immediately with a new klystron type (pulsed, 2.5 MW, 352.2 MHz) that will eventually replace the LEP klystrons (CW, 1.3 MW): one new klystron against 2 LEP klystrons,

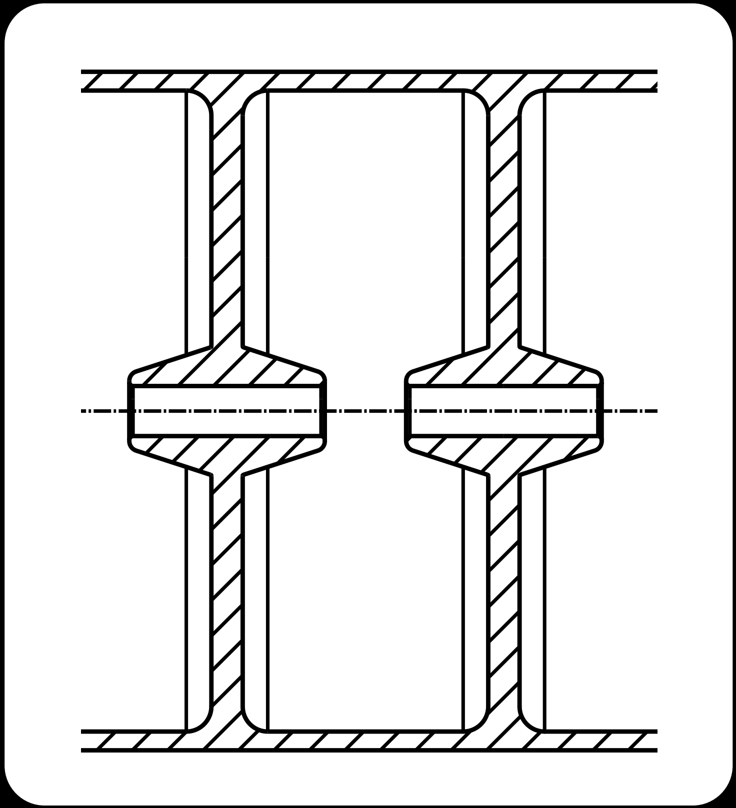
2 critical issues:

during the last review meeting of the HIPPI collaboration 2 items were highlighted by the ESAC:

- worries about the transient behaviour of a π-mode structure versus a π/2 mode structure,
- potential problems with the power splitting from one 2.5 MW klystron to 2 π-mode cavities.

construction I

- the structure consists of discs and cylinders,
- the discs are machined out of solid copper,



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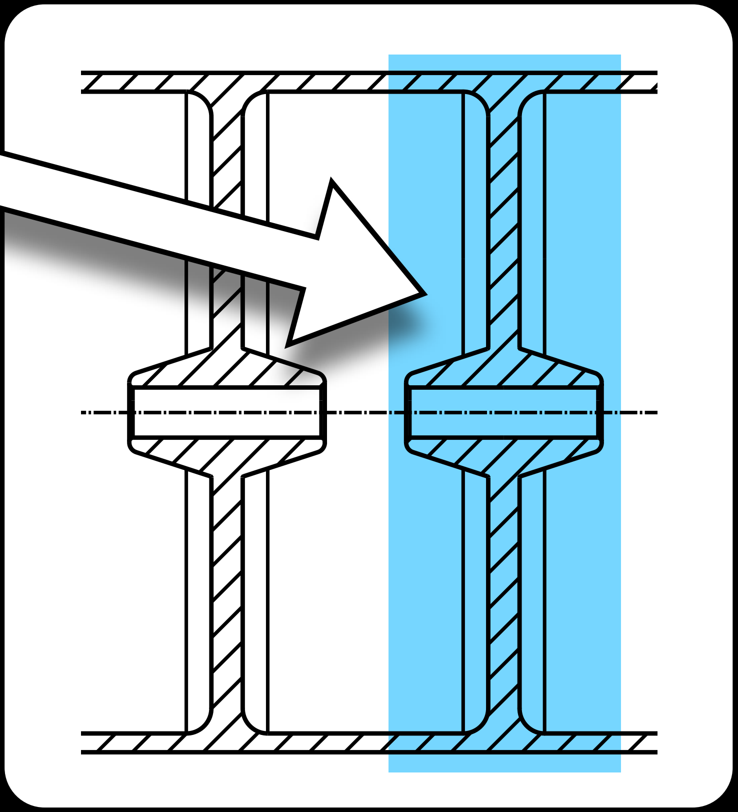
Using cylindric copper pieces we need ≈50 tons of copper (≈ same amount as for SCL 90 - 160 MeV)



construction I

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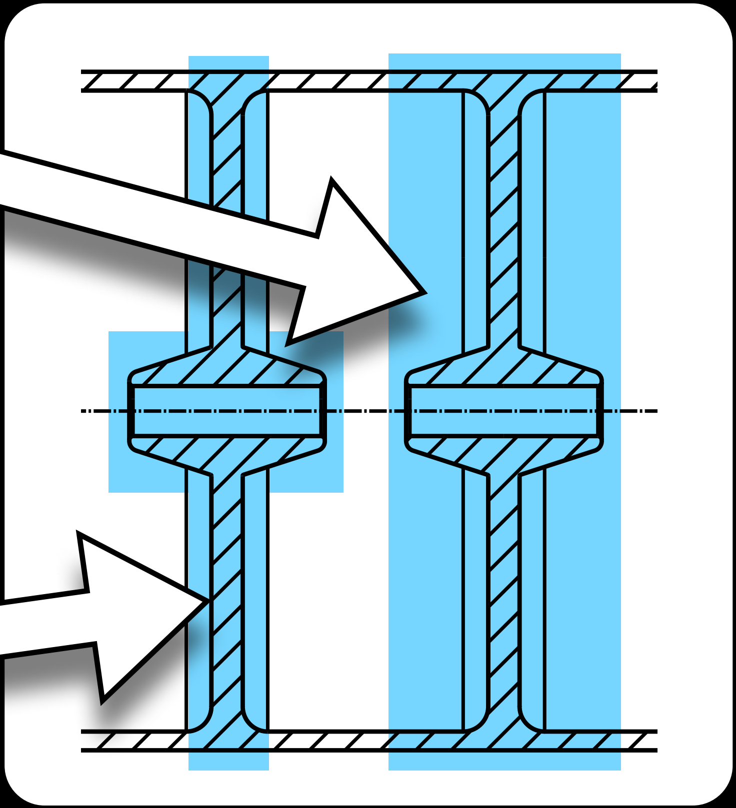
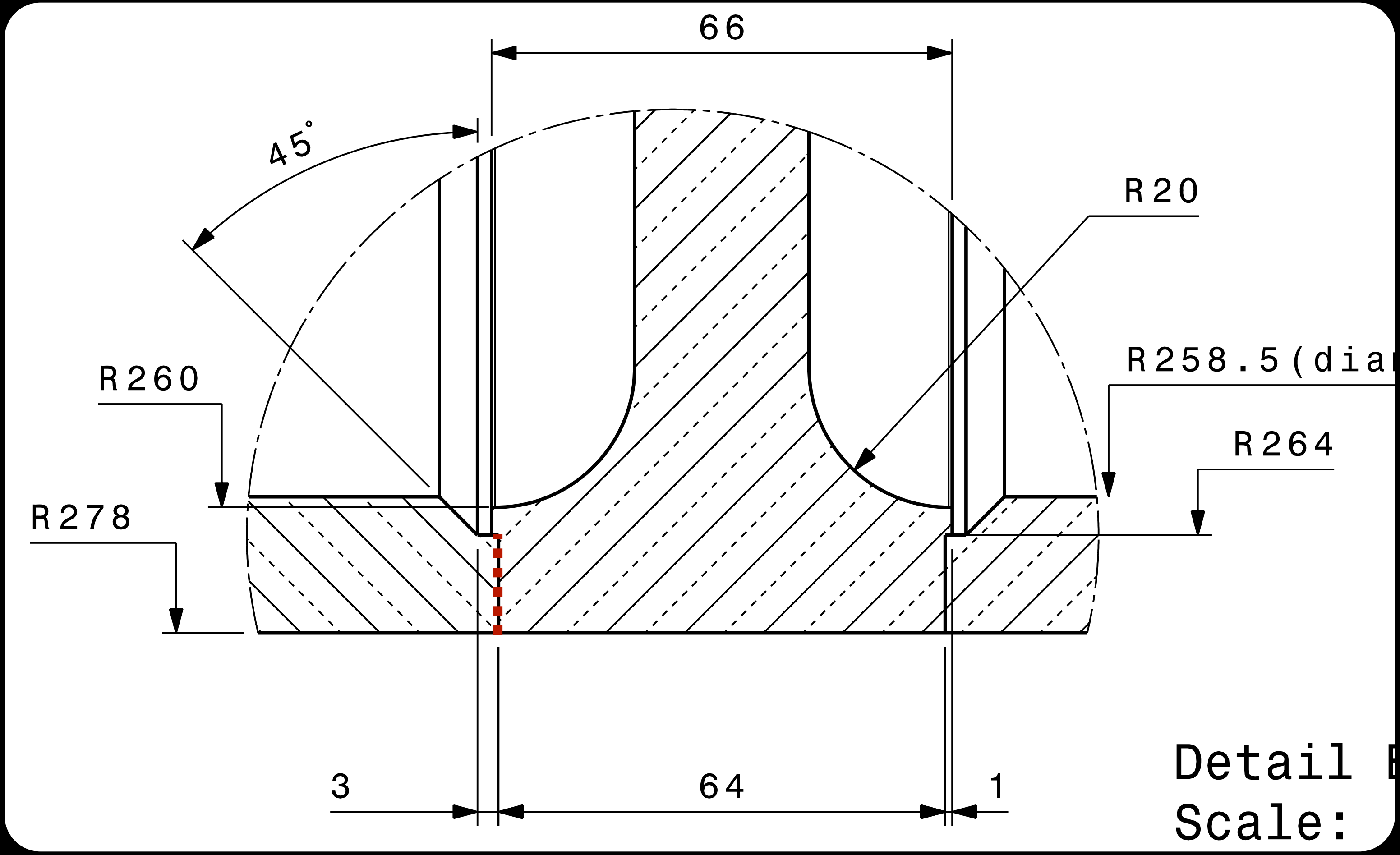
Using cylindric copper pieces we need ≈50 tons of copper (≈ same amount as for SCL 90 - 160 MeV)

With pre-shaped copper pieces we can reduce the amount of copper to ≈36 tons.



PIMS construction II

- cells are e-beam welded from the outside,
- weld with full penetration (~8 mm).



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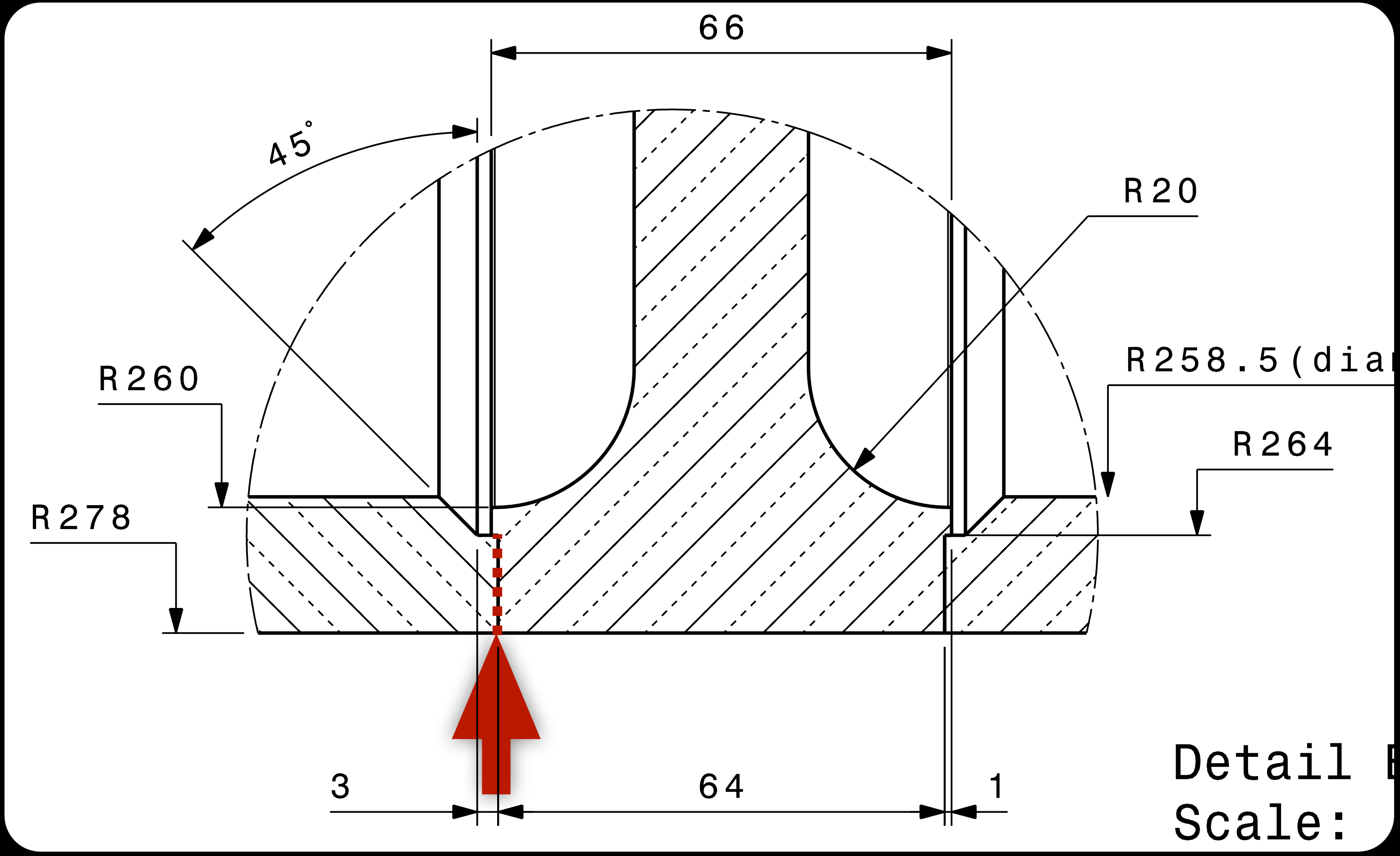


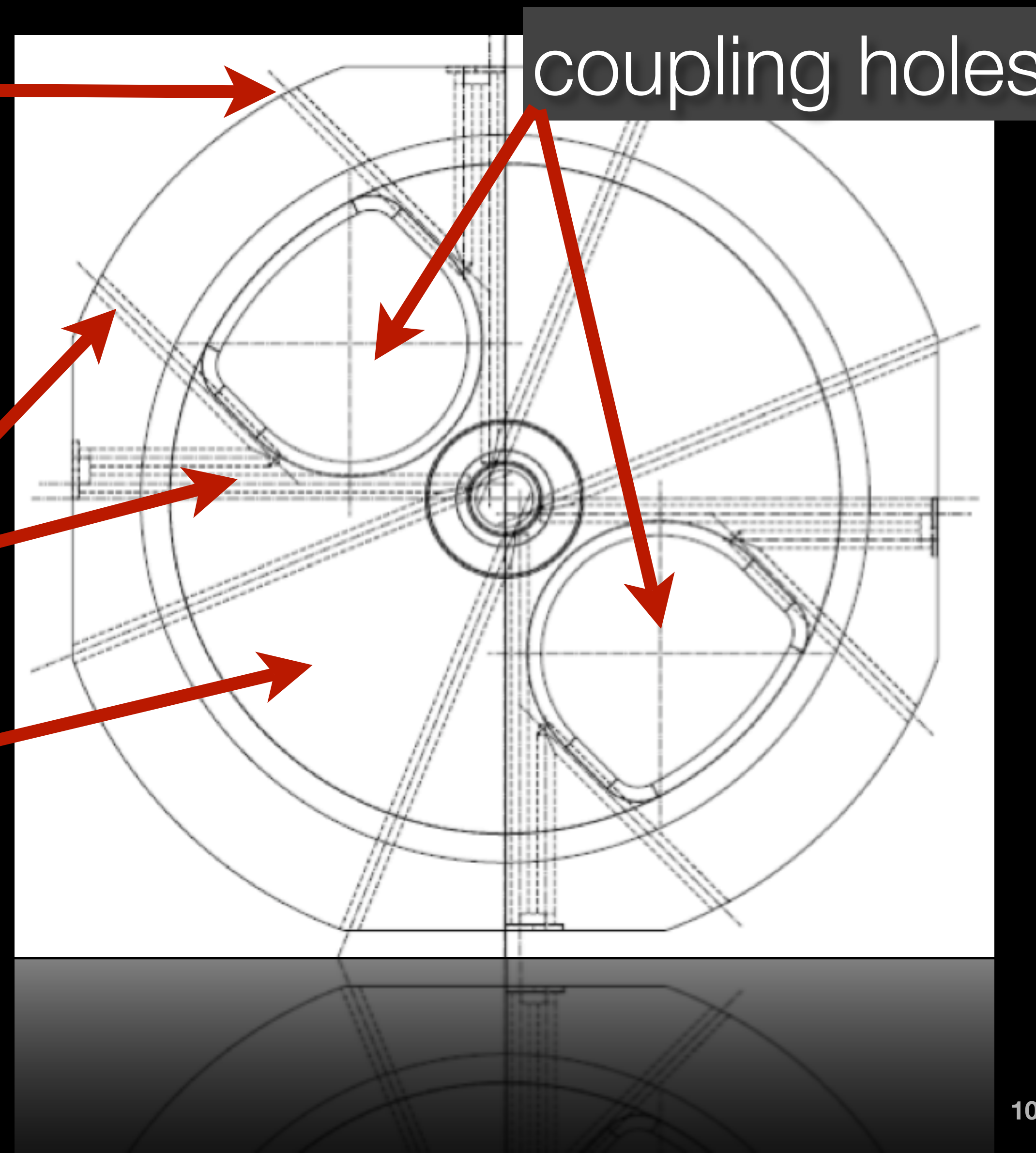
construction III: tank material

Stainless steel (304 L) instead of copper?

Cooling channels are drilled from the outside: no risk of water leaking into vacuum.

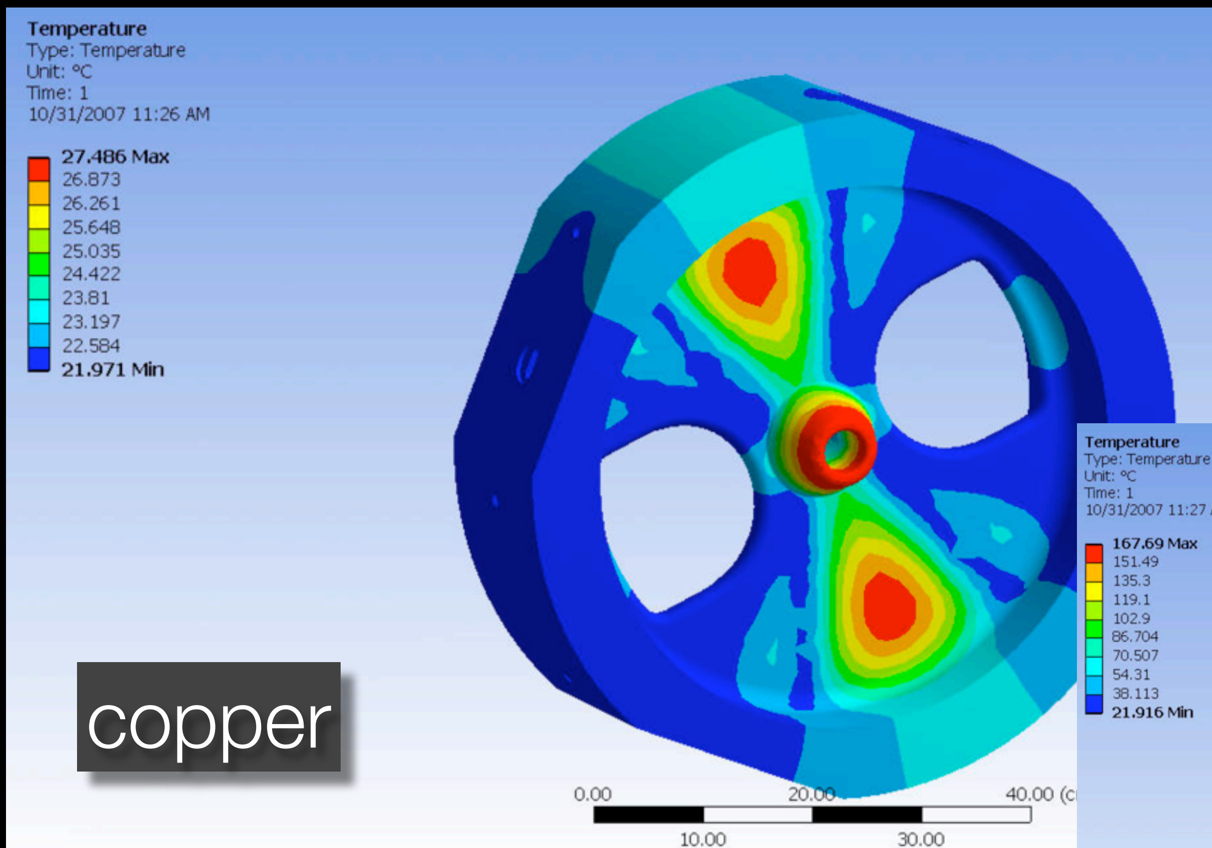
Simplified ANSYS calculation for the cooling of the discs:

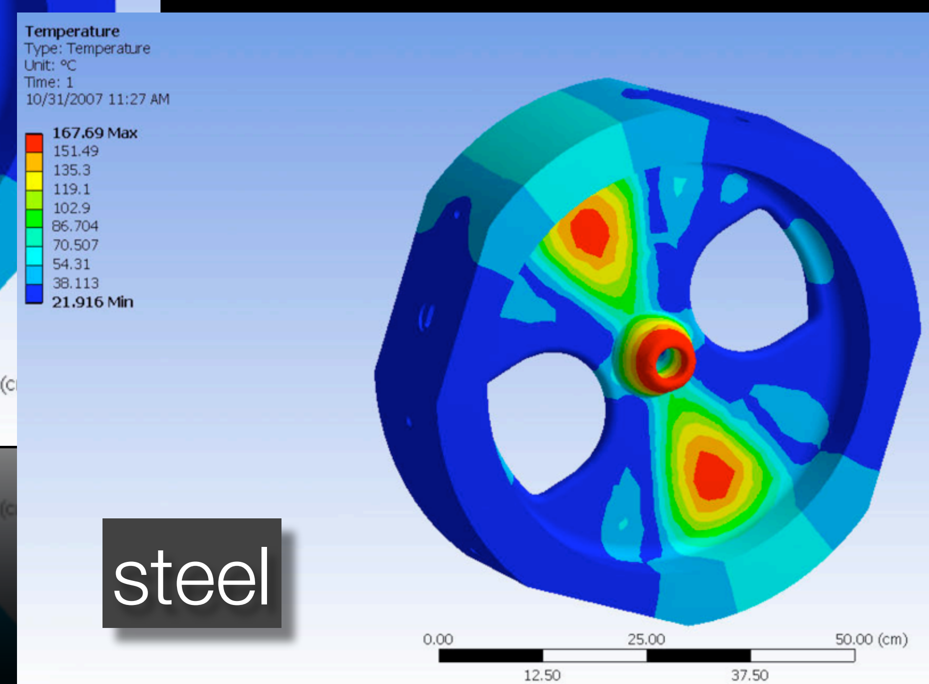
- assume a constant temperature of the water channels (22 deg),
- assume averaged heat distribution on the discs,
- cooling channels still need to be optimised.



max. temperature increase on copper nose (SPL duty cycle): 5.5 deg on steel nose: 146 deg (!)

copper wins!





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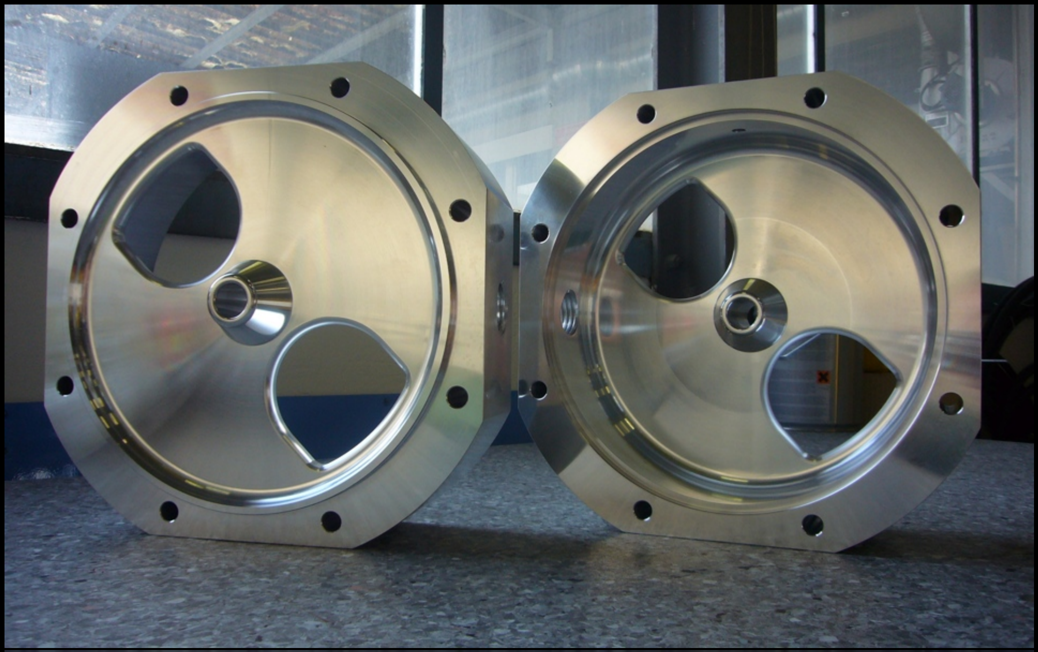
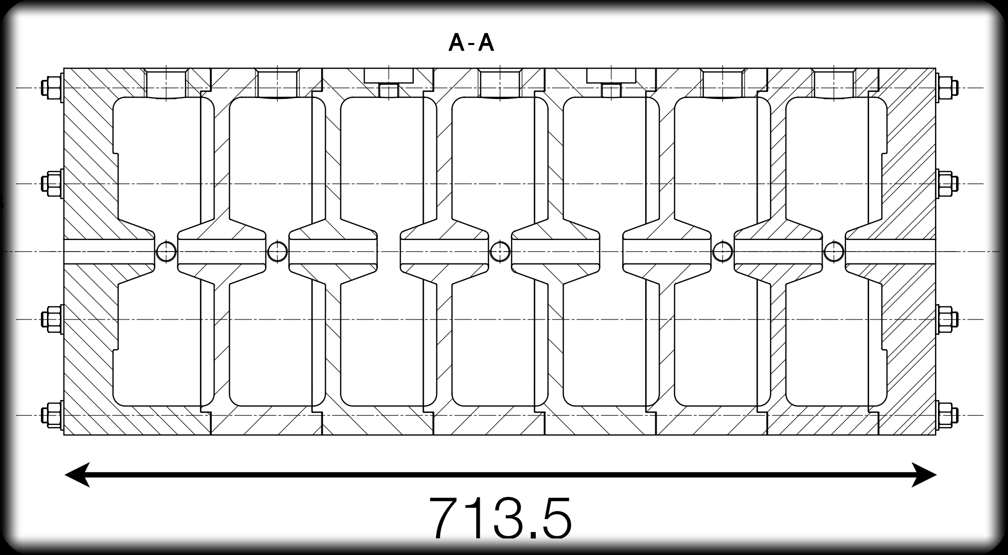
but which kind of copper??

company	copper type	CERN standard	€/kg	total price	date
SISO	3D forged OFE	not yet	16.34	581 k€	June'07
Carlier	3D forged OFE	yes	19.52	711 k€	June'07
Carlier	3D forged OFE	fully	28.83	1056 k€	Dec'07
market estimate	forged OFE	no	~10	~366 k€	Jan'08

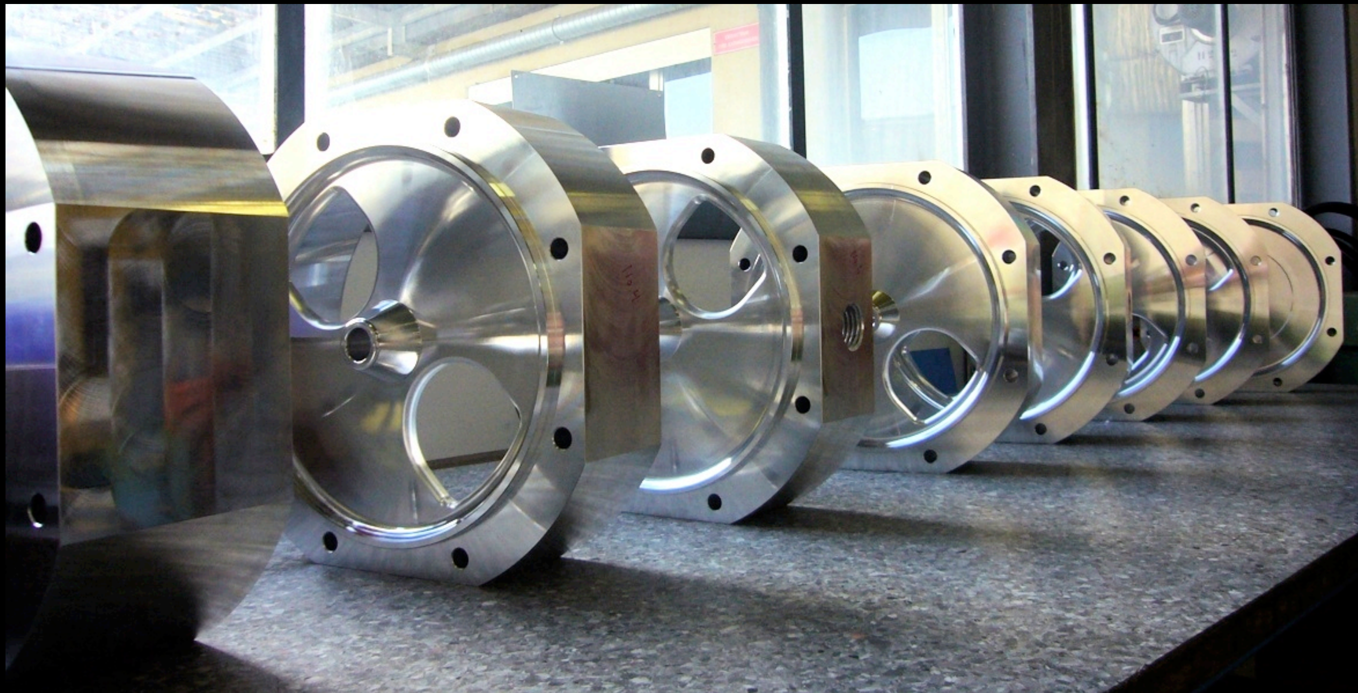
Cold model I





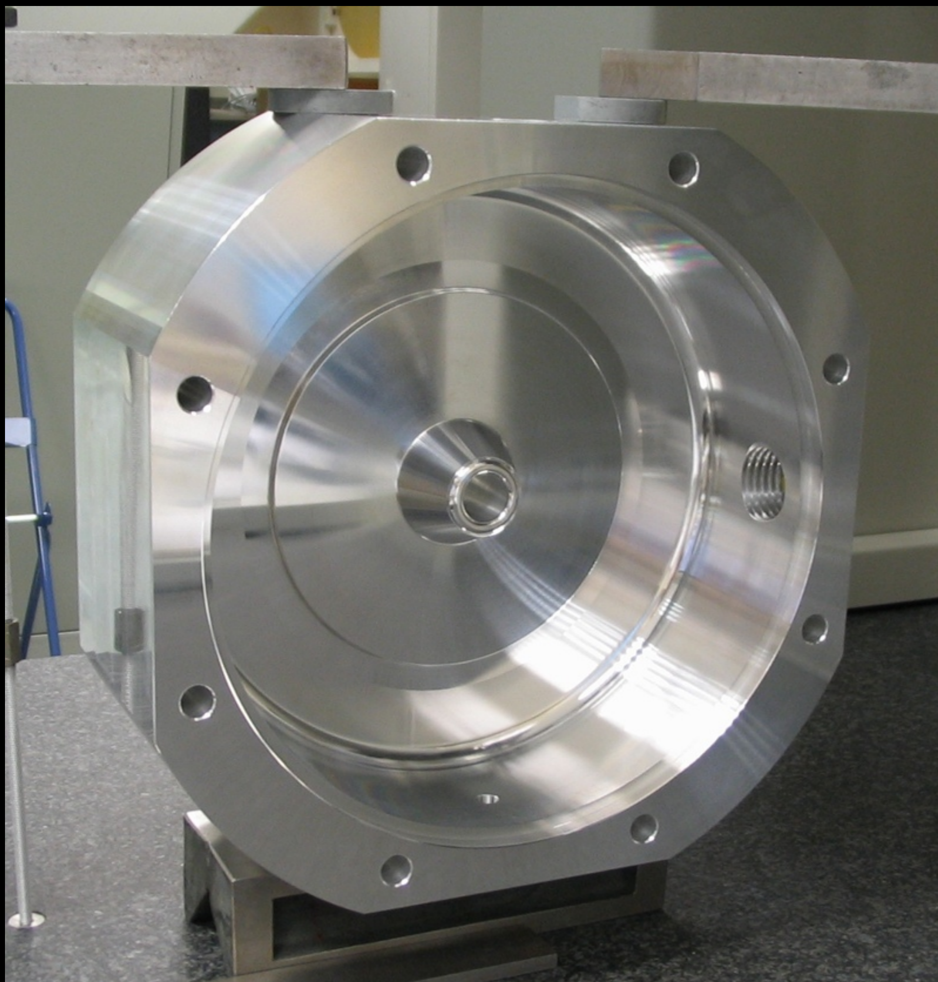
- scaled (704.4 MHz) aluminium model was machined at CERN,
- 7-cell cavity with 5% cell-to-cell coupling,
- 6 identical interior modules,
- model is ready for testing!

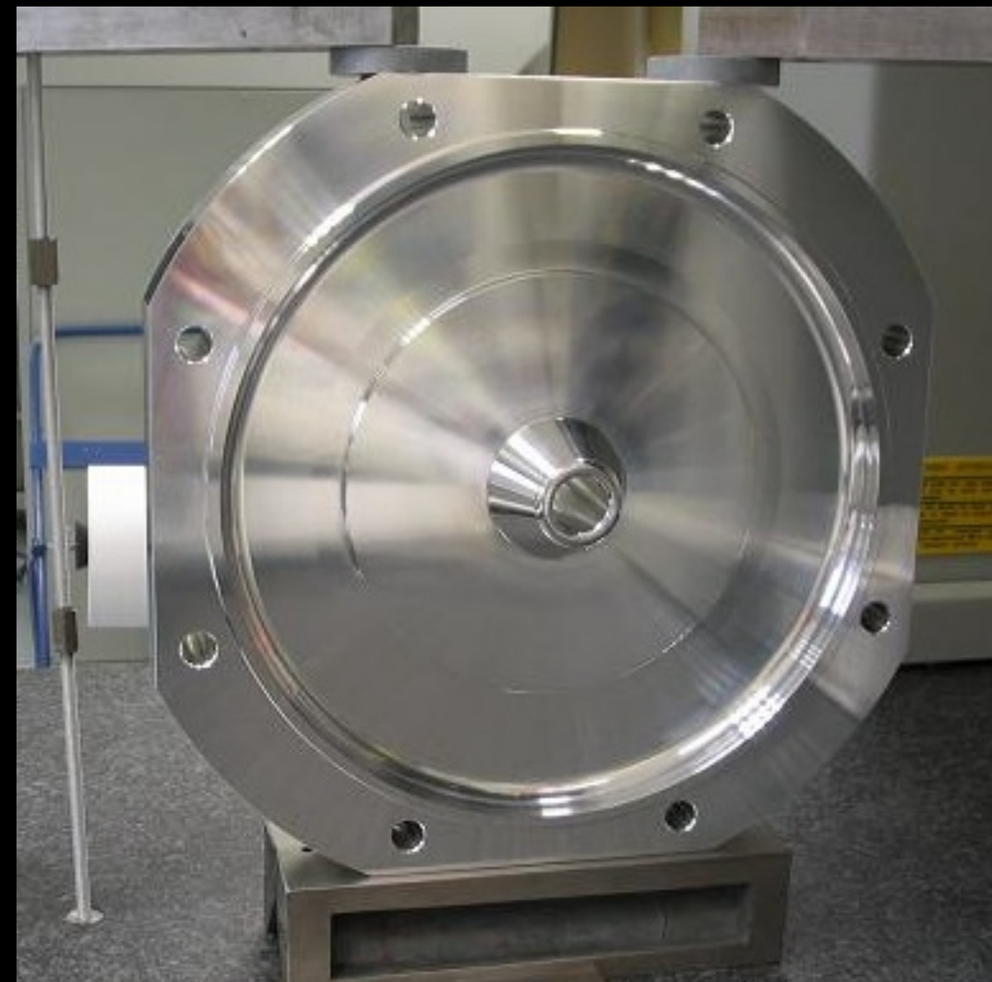
Cold model II



- an additional 3-cell model with 3% coupling is under construction for comparison with 3D simulations (coupling, R/Q),
- the interior modules can be exchanged to test a different slot shape,

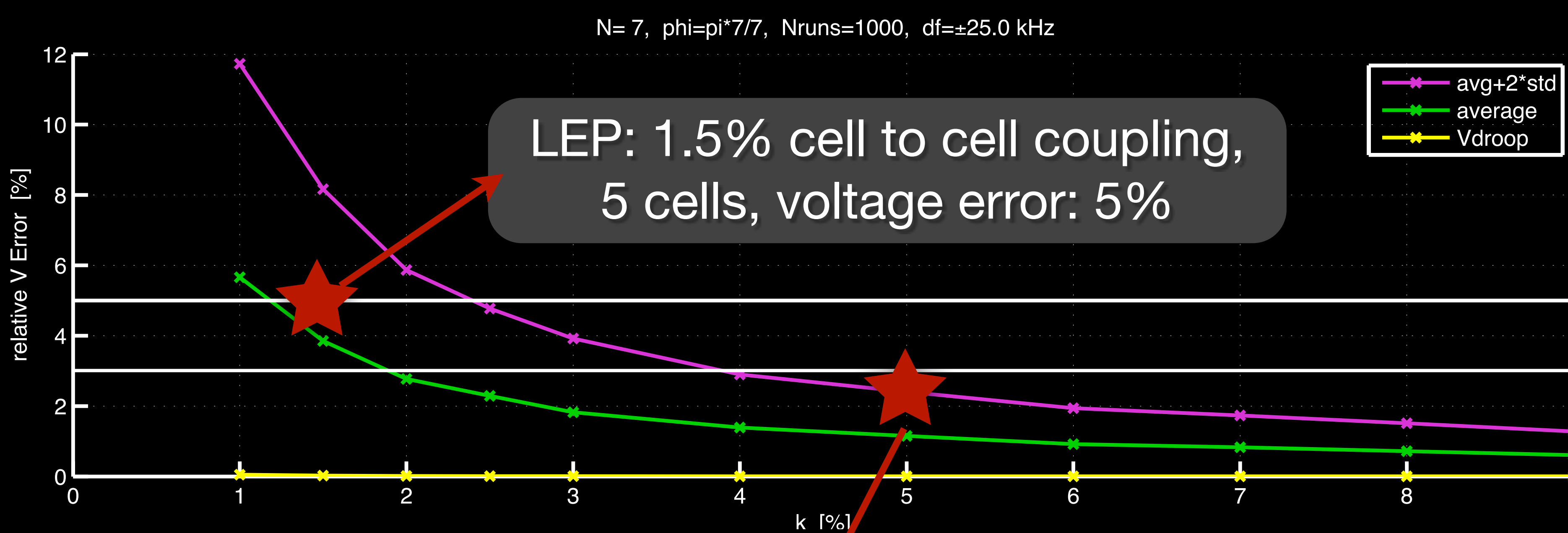
Cold model: end cells





frequency errors

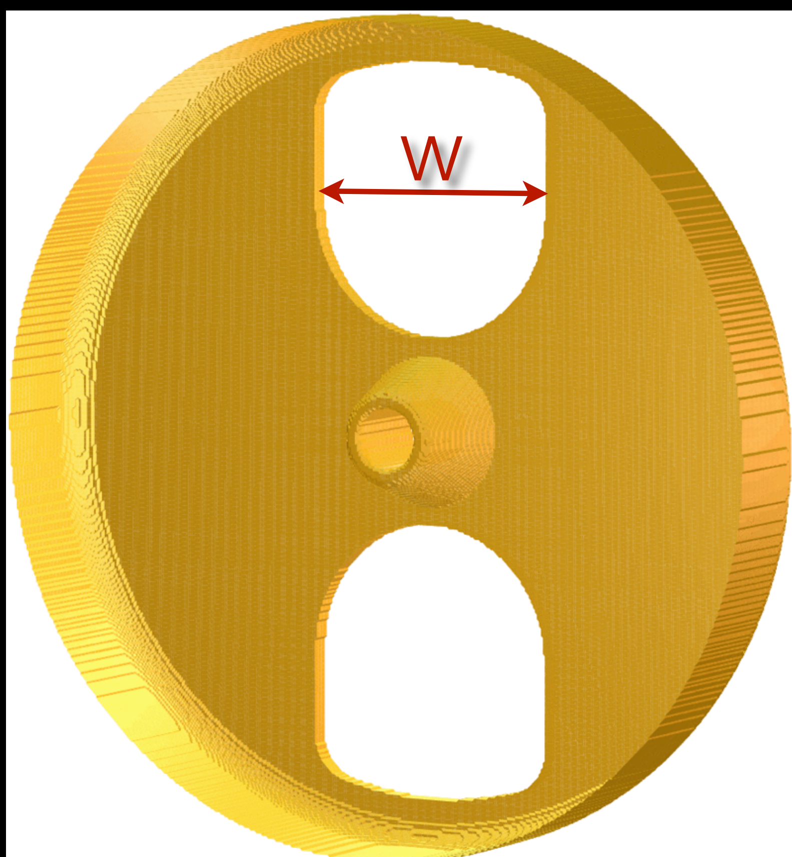
- 7 cell pi-mode structure analysed with a circuit model (terminated & non-terminated end-cells), using 10^3-10^4 different error cases,
- assume frequency errors per cell linearly distributed between -25 kHz/+25 kHz,



Linac4: 5% cell to cell coupling, 7 cells, for 95% of all runs: voltage error < 3% (including end-cell tuning)

coupling errors

the voltage variation from cell to cell is also influenced by errors in the cell-to-cell coupling factor:



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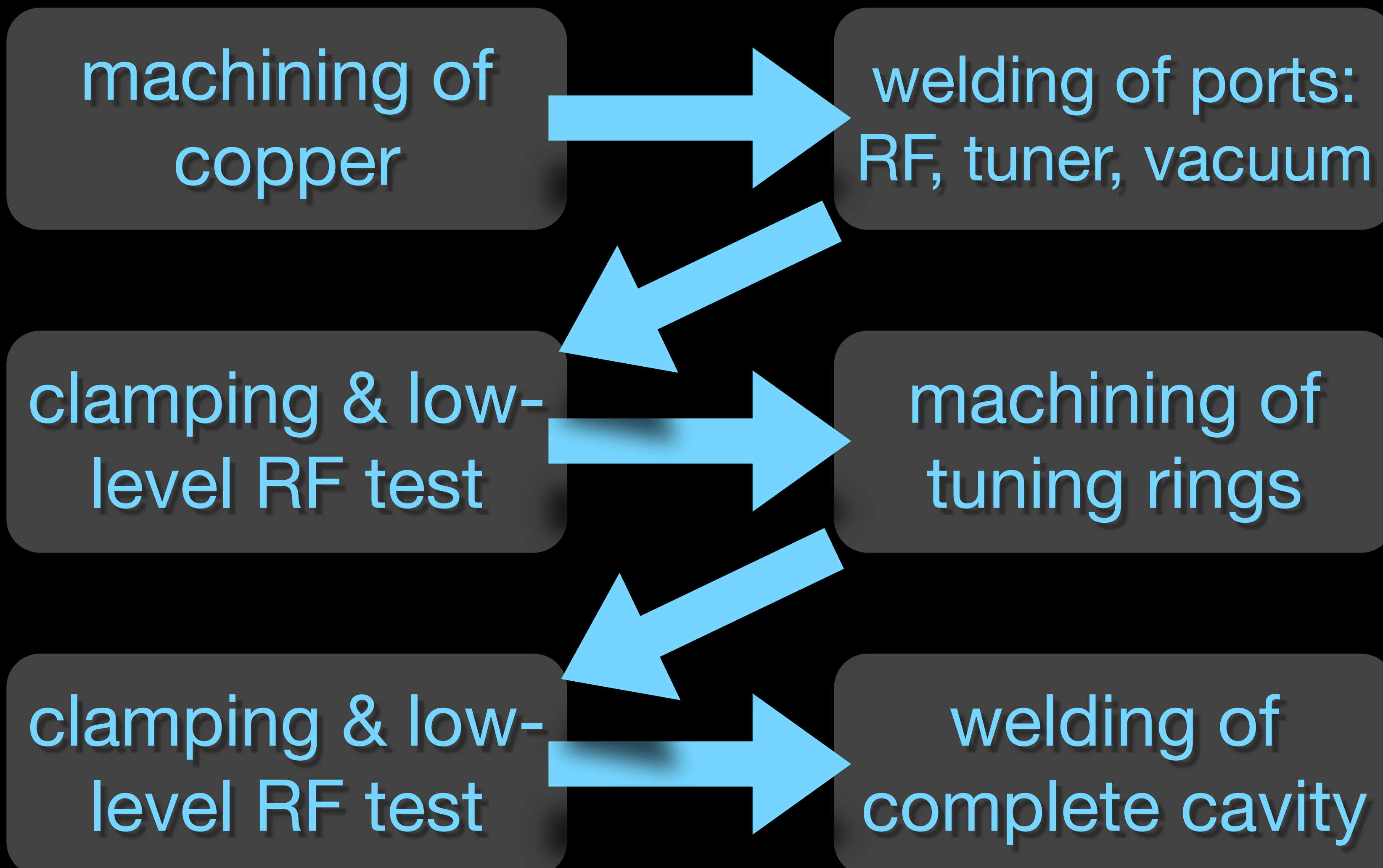
- the coupling constant *k* is mainly influenced by the width *w* of the slot,
- from the equivalent circuit analysis one finds that a 1/1000 change in *k* results in an average voltage error of ~1% in each cell,

➡ tolerance for *w*: 172 mm ±0.05 mm

summary on frequency errors

	max. freq. error	tolerance	comment	correction
3D + 2D simulation	352.2 ± 0.25 MHz	0.5 mm in radius	systematic	remachining/ tuning
machining	± 200 kHz	20 - 50 µm	random	remachining/ tuning
e-beam welding	< -100 kHz	?	systematic	design
vacuum	-20 kHz	10 µm	systematic, end-walls	design
vacuum	+114 kHz	-	systematic, air/vacuum	design
warming up	-60 kHz	10 deg	systematic	tuning

Construction steps



no brazing operation on the cavity!

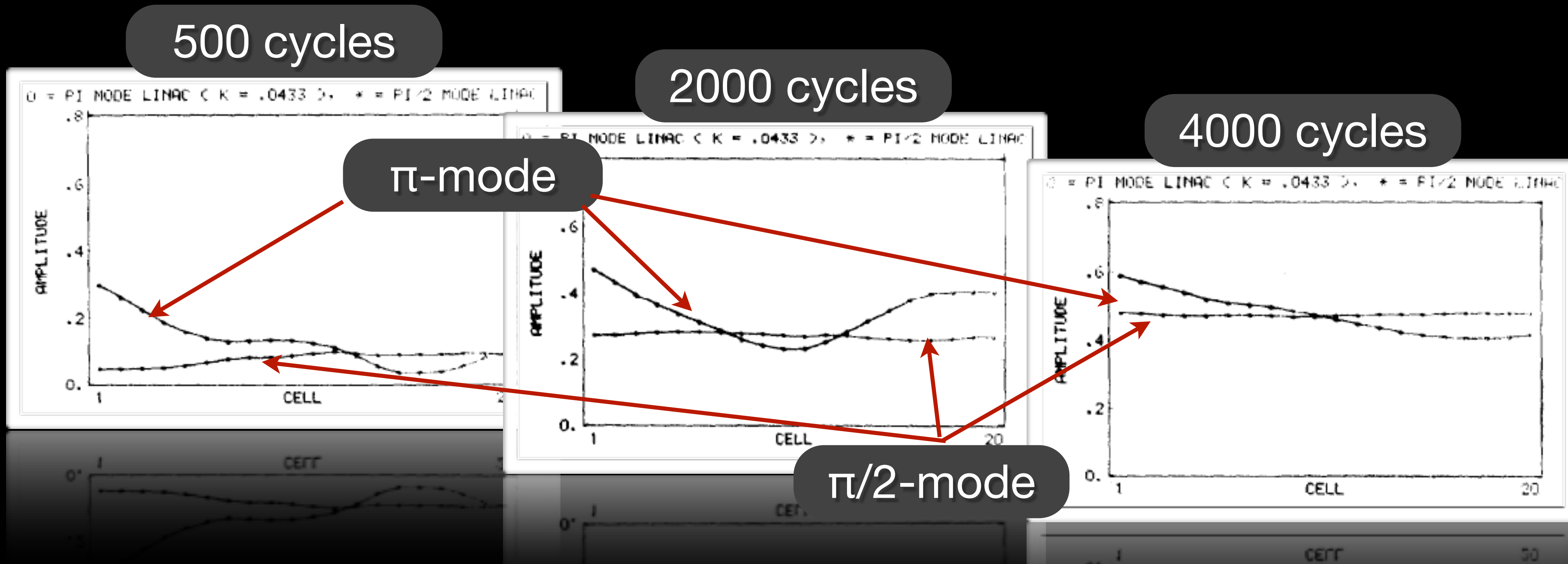
tuning strategy

- **tuning ring** across the circumference of the discs to allow for a frequency correction of ±0.5 MHz, ➜ correction of machining errors before the welding of the structure,
- maximum **tuner** diameter at low energy: 62 mm, **5 fixed tuners + 2 movable tuners**, for higher energies 2 tuners per cell or increase the diameter of the tuner, tuning range: ±0.5 MHz ➜ correction of temperature effects, spread in welding contraction (should be very small), mechanical deformation during installation,
- final errors expected to be < ±25 kHz (confirmed by LEP experience).

➜ will be revised after the results from the hot model

beam loading & transient behaviour

- **1967**: Nagle, Knapp, Knapp present their resonant circuit model for coupled resonators,
- **1969**: Knapp compares the filling of a π/2 mode cavity with that of a π mode cavity: 20 cells, asymmetric feeding from the left

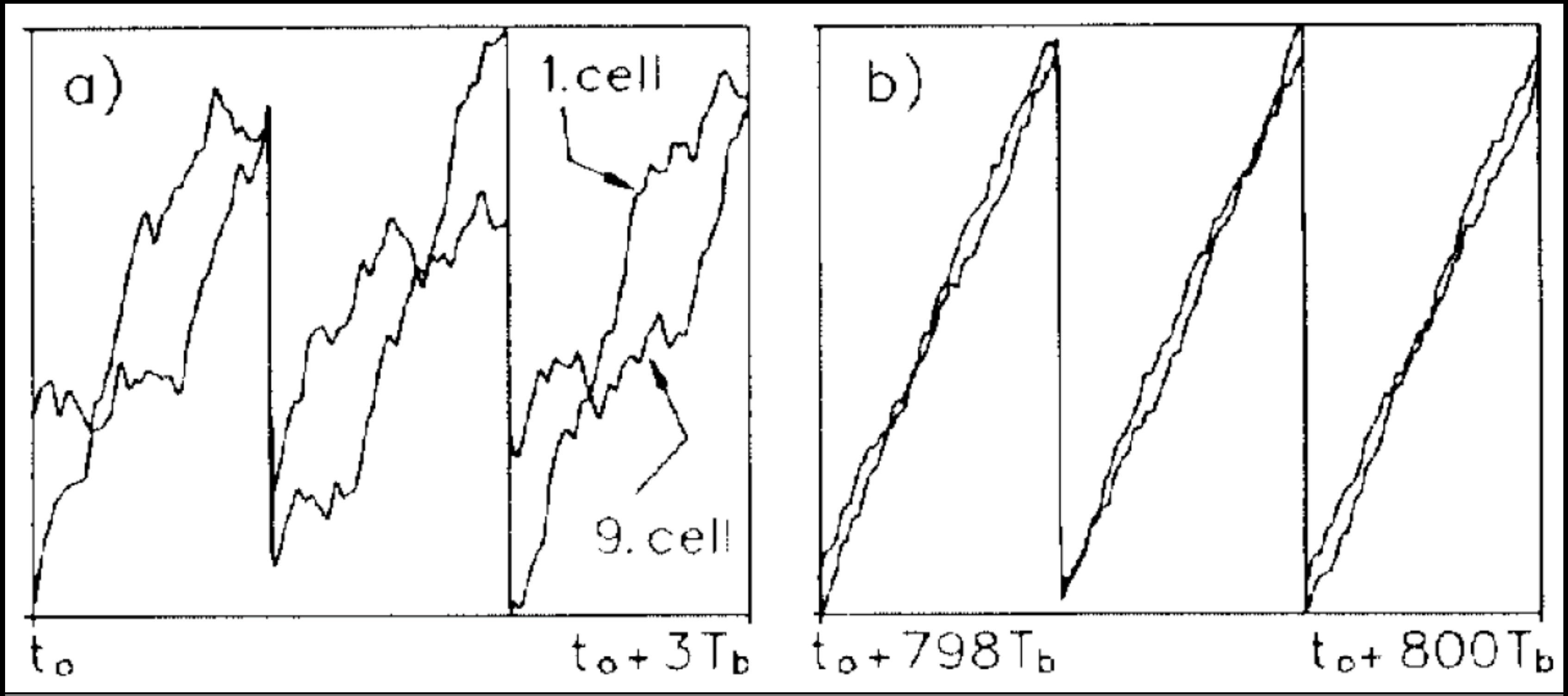


conclusion:

Assuming the same number of cells, and an asymmetric feeding point: during the filling of the cavity, the cell voltage rises much more evenly in a π/2-mode structure than in a π-mode structure.

why do SC multi-cell π-mode cavities work?

- **1993** Henke & Filtz: beam loading in an asymmetrically fed 9-cell TESLA cavity: voltage profile in the first and last bunches of τ_f (filling time: 0.8 ms)

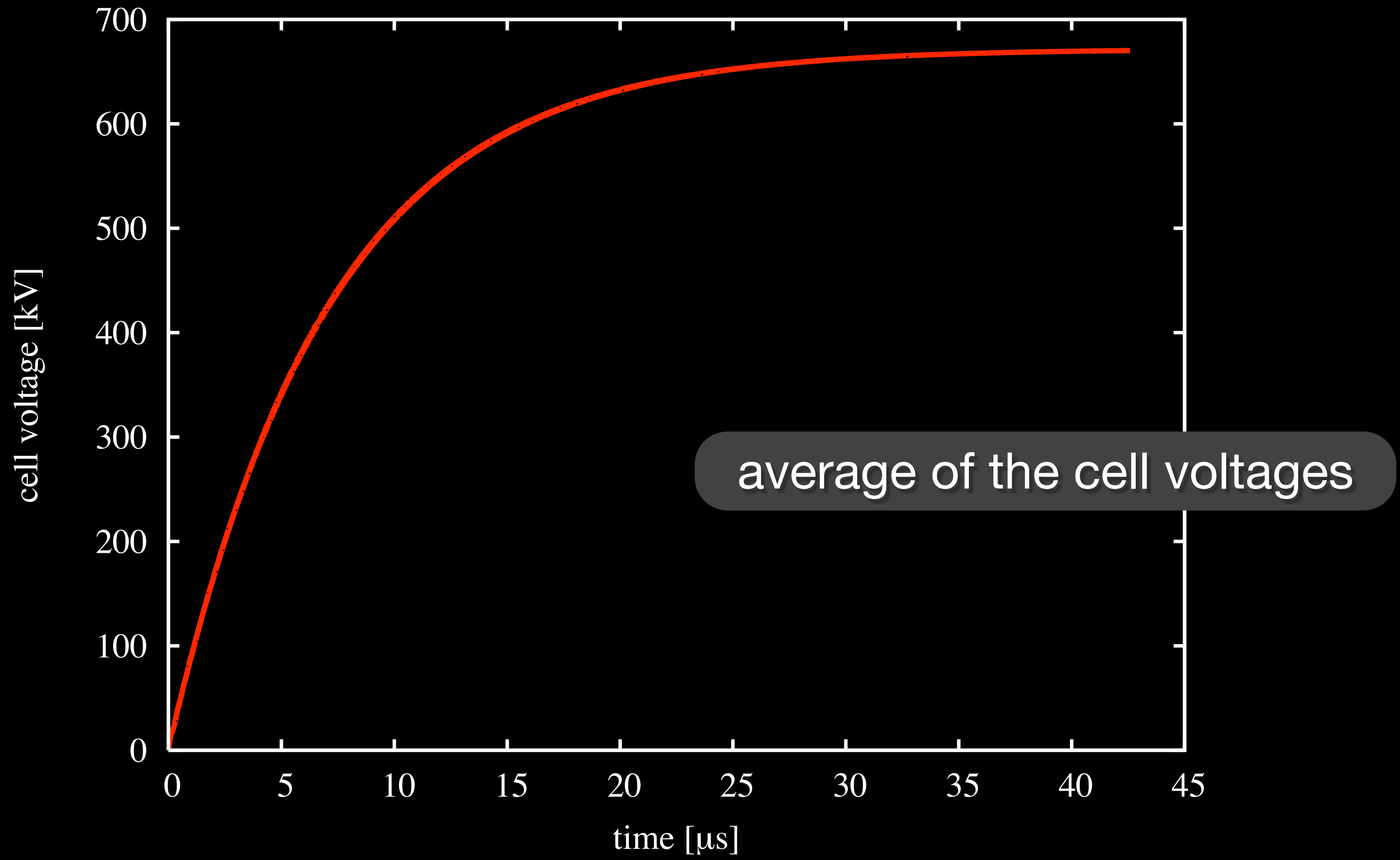


conclusion:

during the transients:

- confirmation of Knapp: the voltage profile in the different cells is different,
- the average voltage gain over the 9 cells only changes up to a maximum of 0.05 %.

filling process for the Linac4 7-cell π-mode structure



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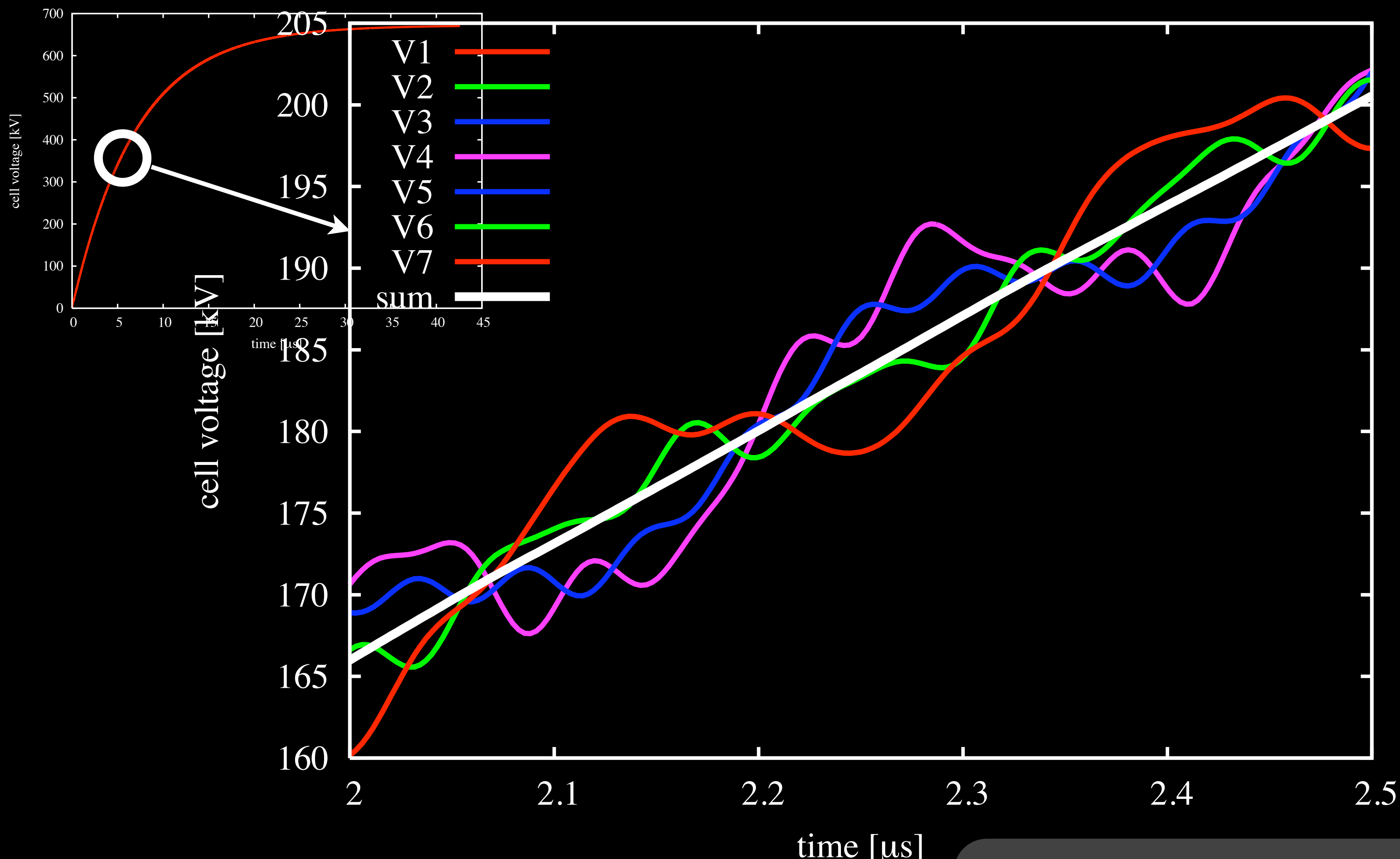

difference of cell voltages

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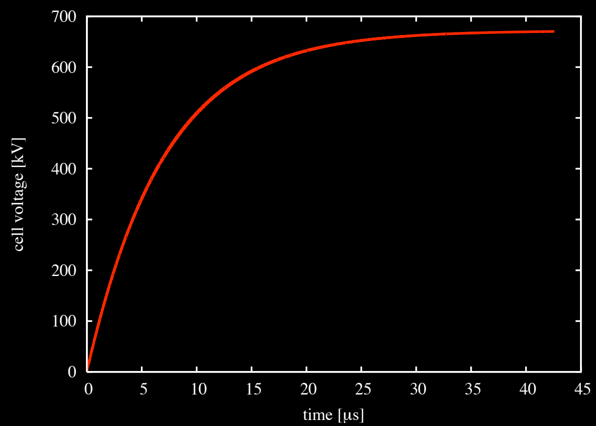
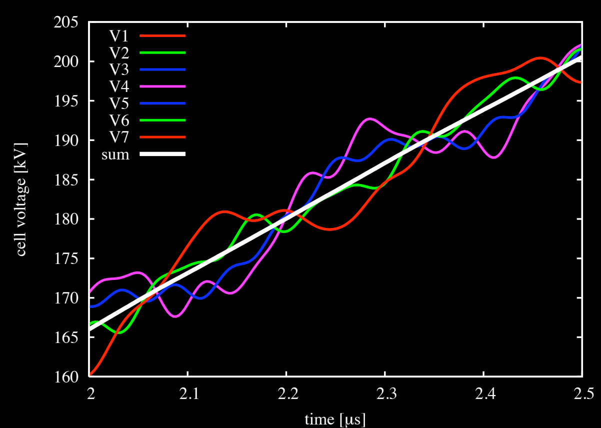
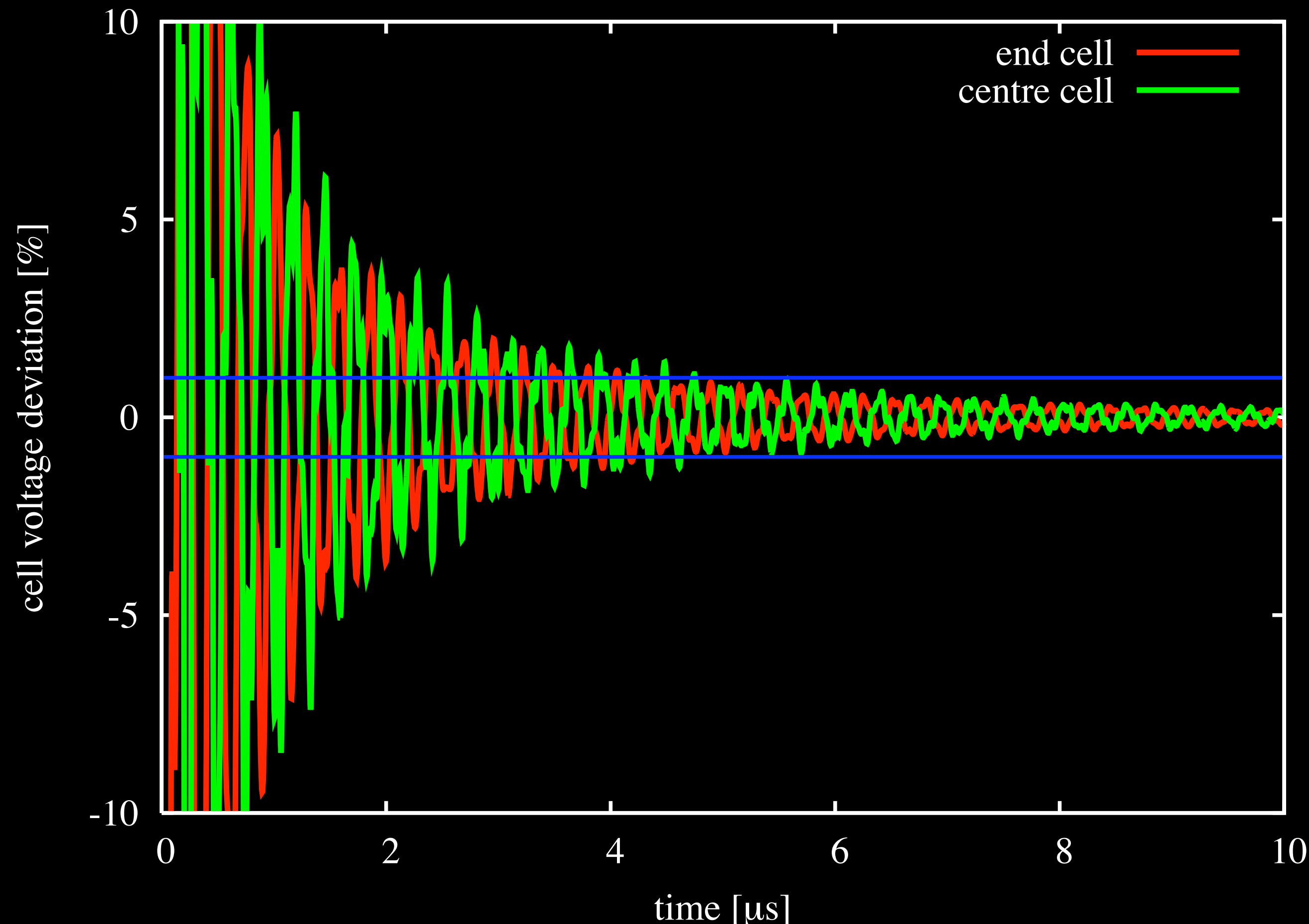
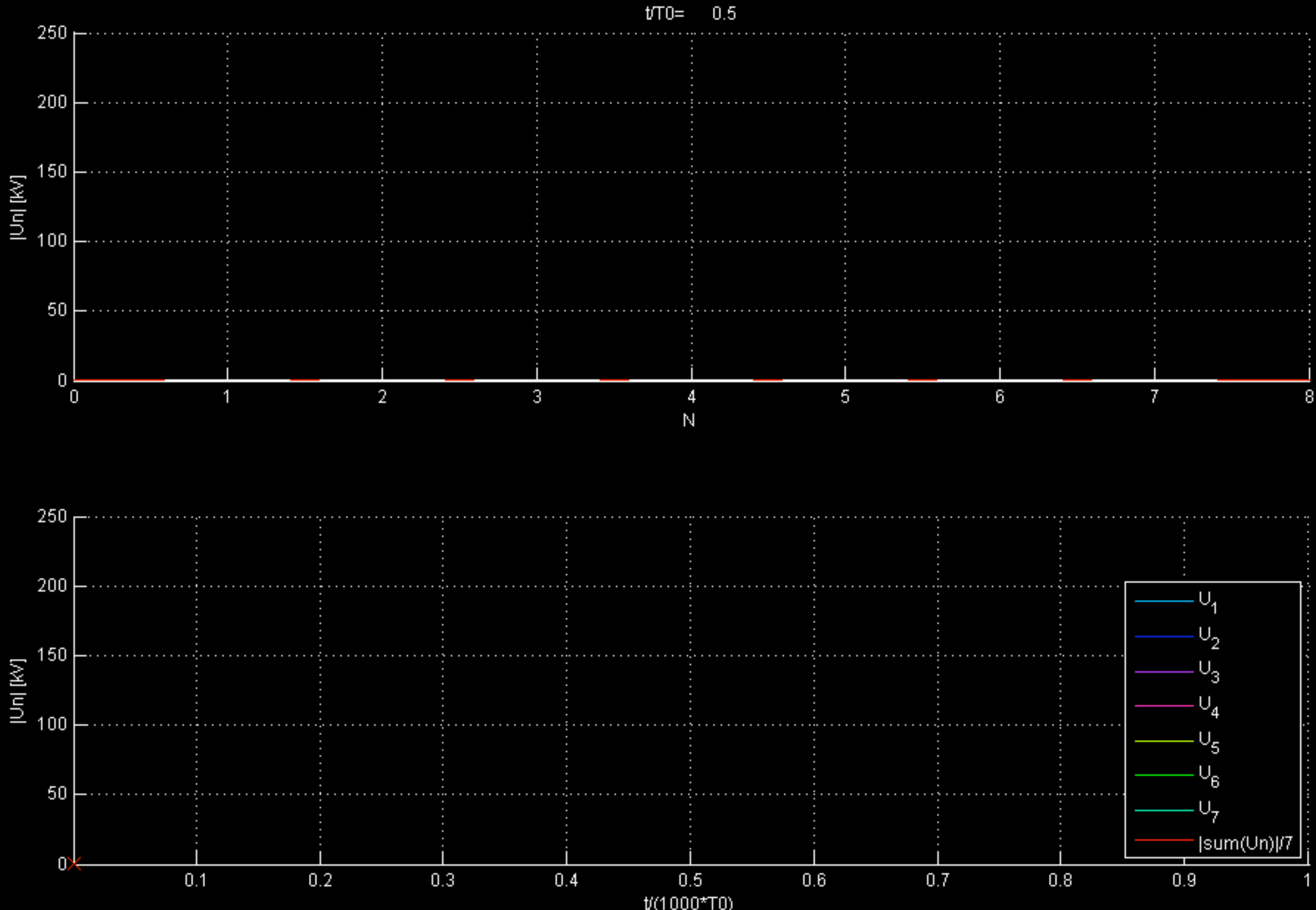




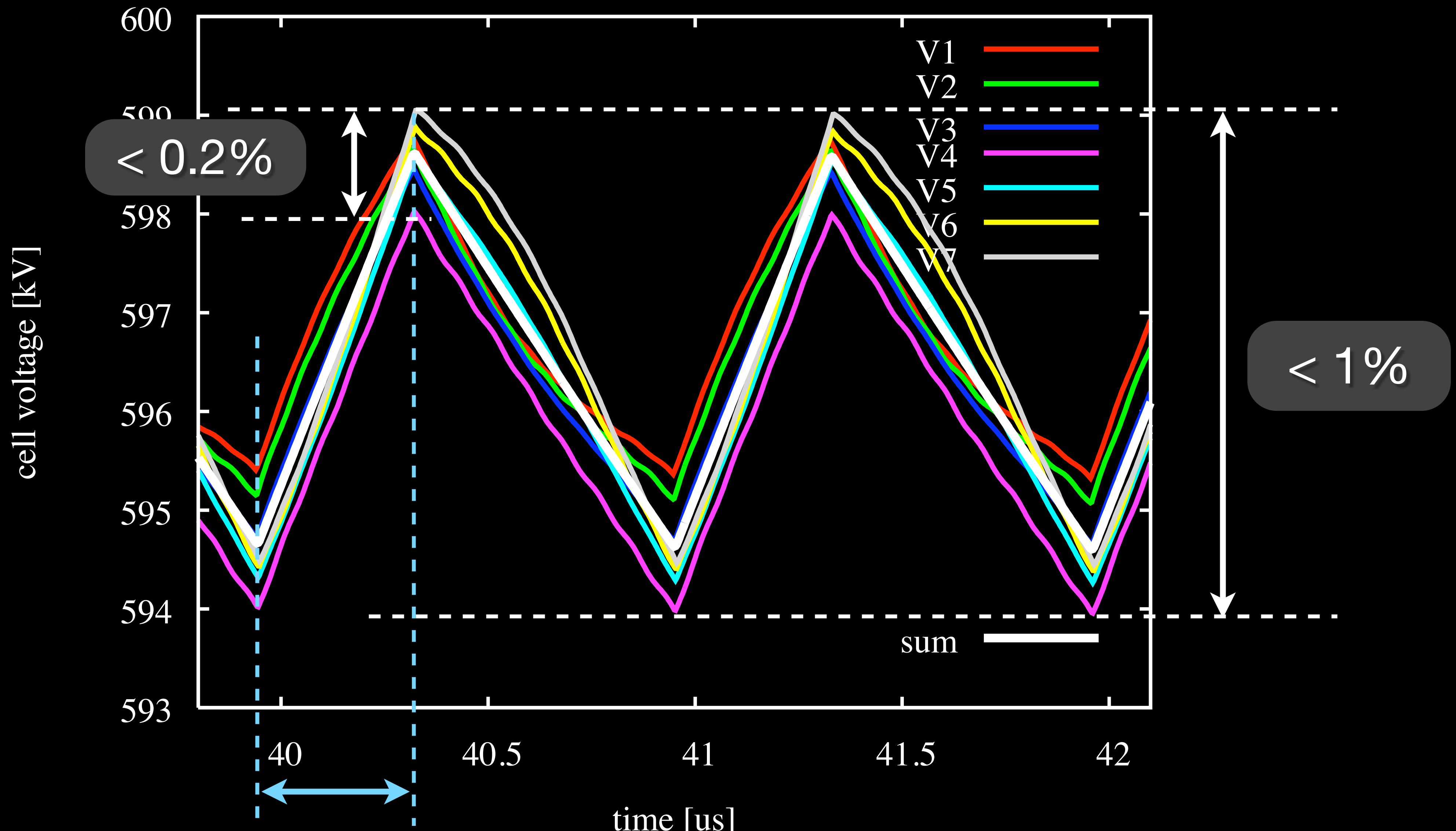


difference of cell voltages



t/T0= 0.5
|Un| [kV]
N
t/(1000*T0)
U1
U2
U3
U4
U5
U6
U7
|sum(Un)|/7

beam loading...



chopping period: 133 out of 255 bunches

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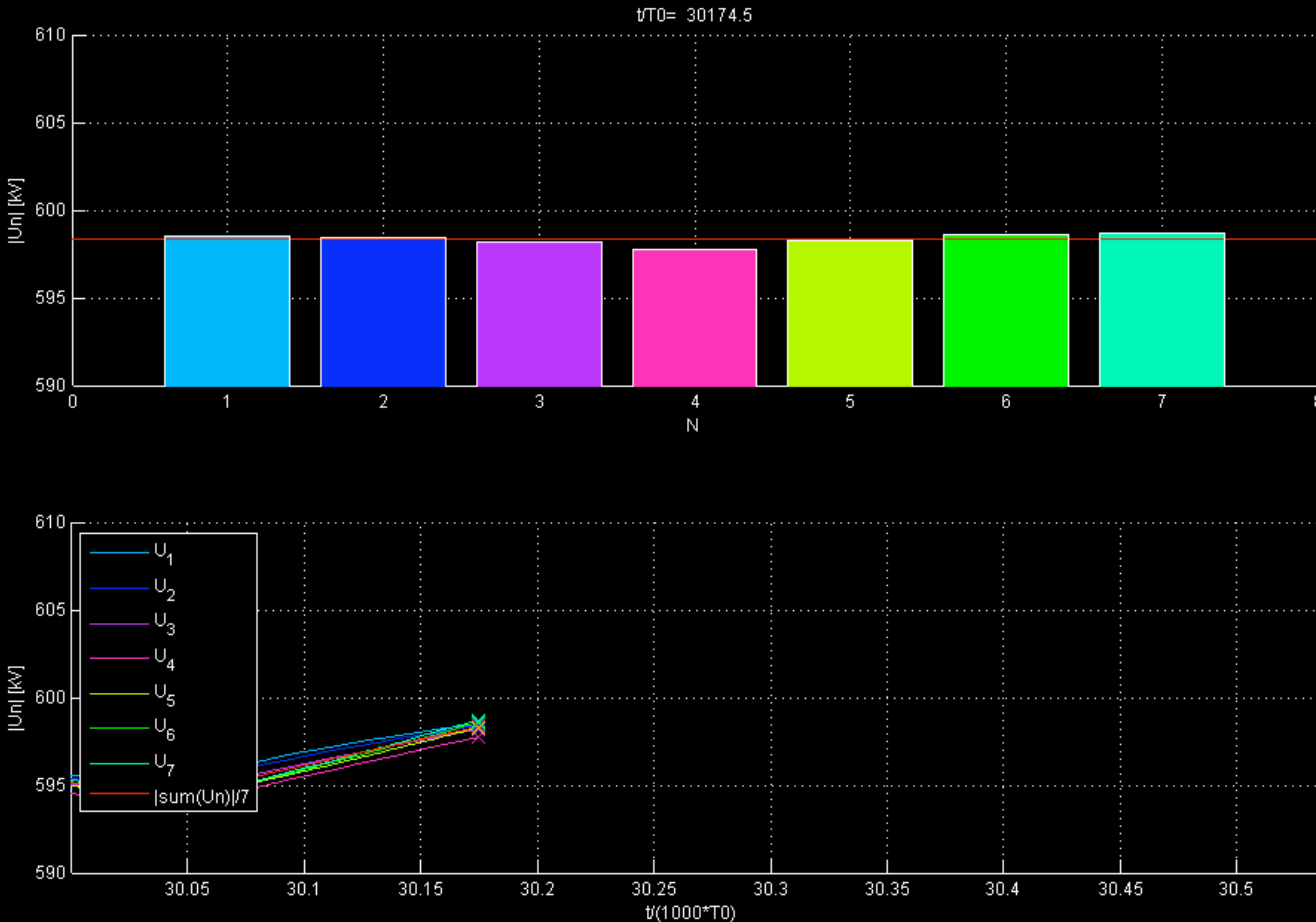

t/T0= 30174.5
|Un| [kV]
610
605
600
595
590
0 1 2 3 4 5 6 7 8
N
|Un| [kV]
U1
U2
U3
U4
U5
U6
U7
|sum(Un)|/7
30.05 30.1 30.15 30.2 30.25 30.3 30.35 30.4 30.45 30.5
t/(1000*T0)

conclusion I: on cavity filling

- with a loaded Q of <8000, the filling time is of the order of $\tau_f = 7\mu s$ ($2^*Q_l/\omega$),
- during the filling process the cell-fields are slightly different but change symmetrically to the feeding point,
- the time to get a stable voltage from the power converters is in the order of 50 µs,
- during the filling of the cavity and the stabilisation of the cavity voltage, we will dump unusable beam on the distributor head-dump,

no disadvantage in using the π-mode

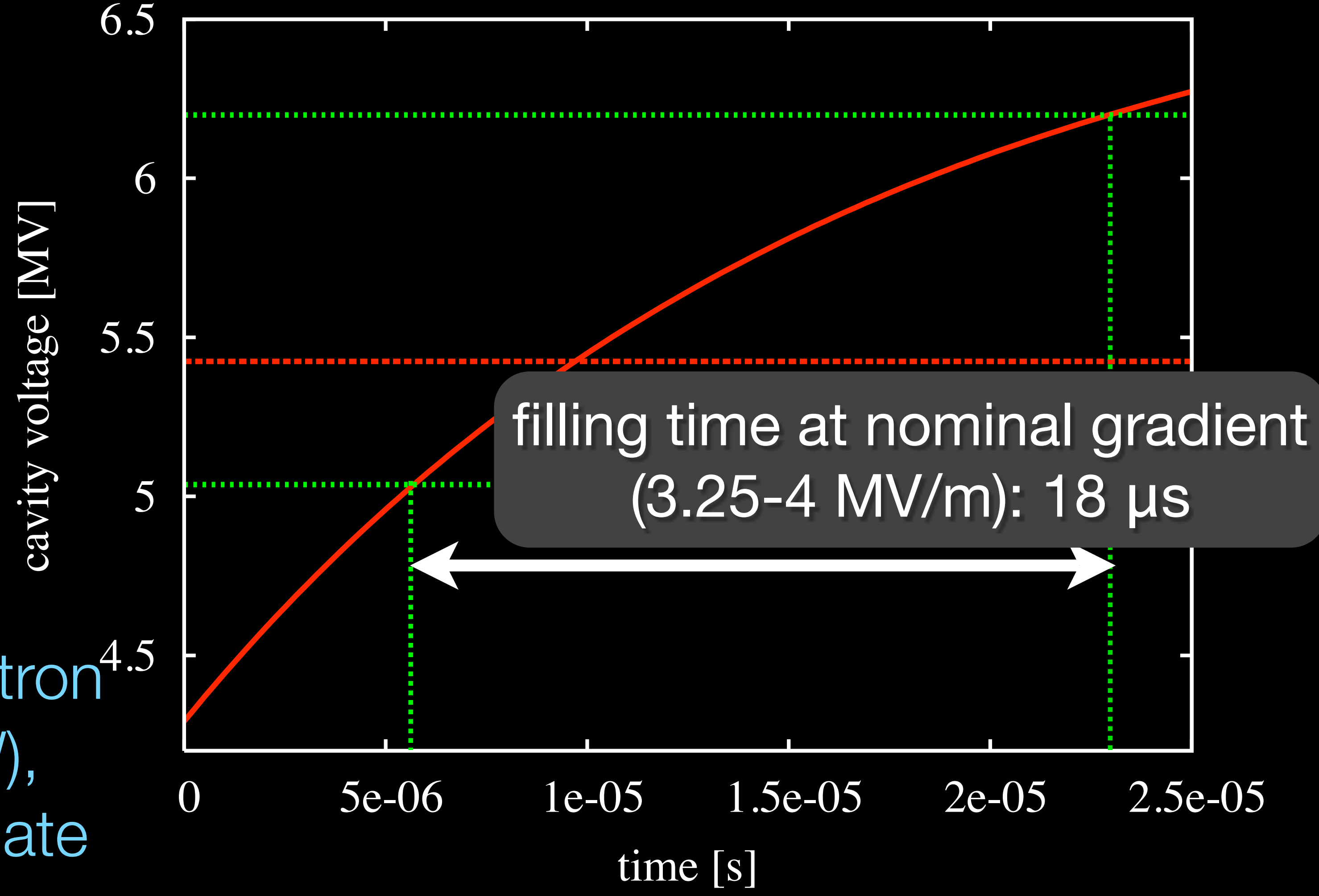
conclusion II: on transient beam loading effects

- with beam loading taken into account in one cell after another with correct time delay: the cell voltages are no longer symmetric to the feeding point,
- but with the Linac4 chopping cycle (122 out of 355) the voltage differences are below 1%,
- as for the filling process: the average voltage gain over the 7 cells is basically constant (<< 0.1 %),

again: no disadvantage due to the use of the π-mode

energy ramping 159 - 161 MeV

The PSB painting scheme requires 2 MeV energy change within 10 **µs**:

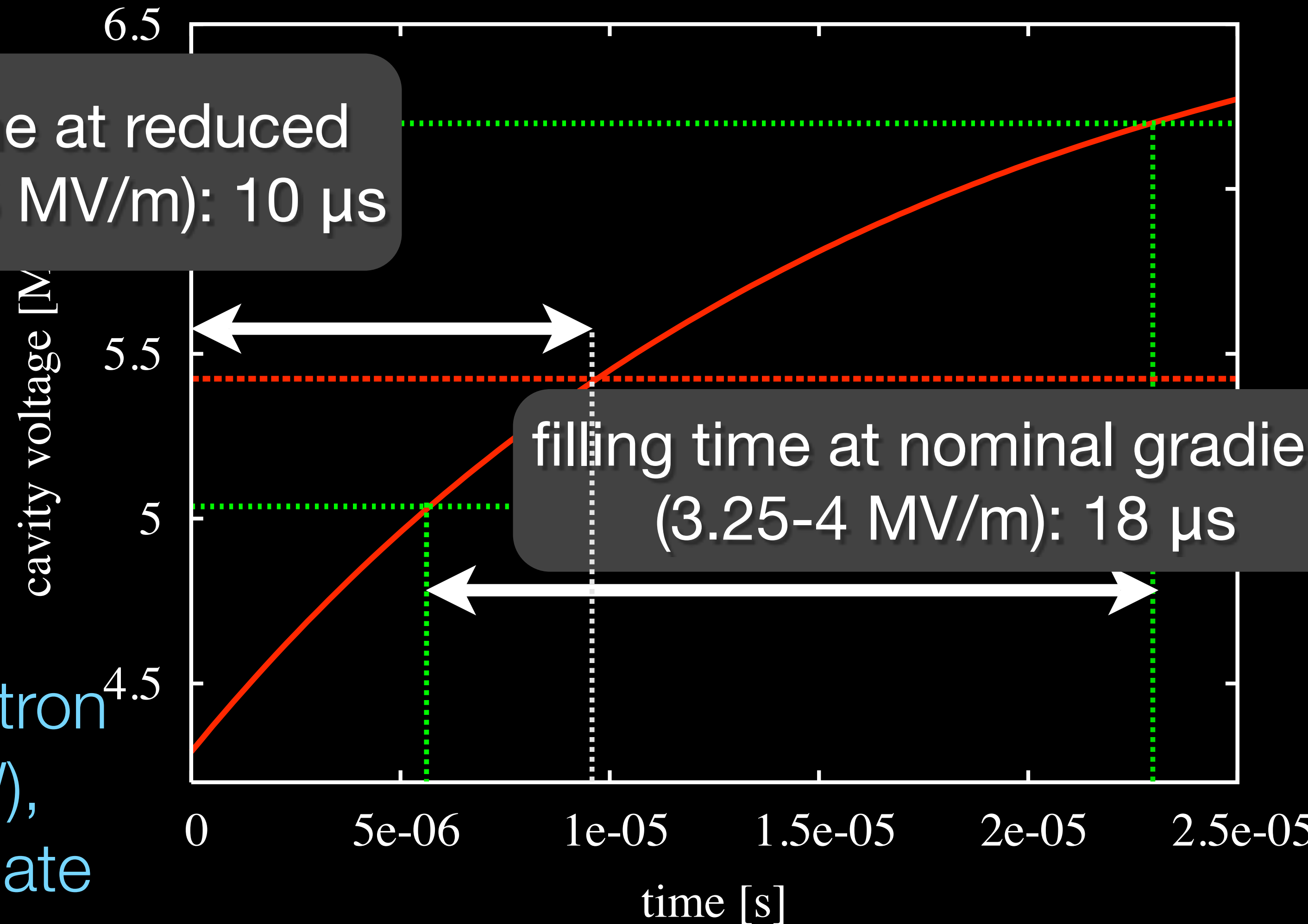


Cavity filling assuming full klystron power (1.3 MW), pessimistic estimate

energy ramping 159 - 161 MeV

The PSB painting scheme requires 2 MeV energy change within 10 μs:

shorter filling time at reduced gradient (2.77-3.5 MV/m): 10 μs

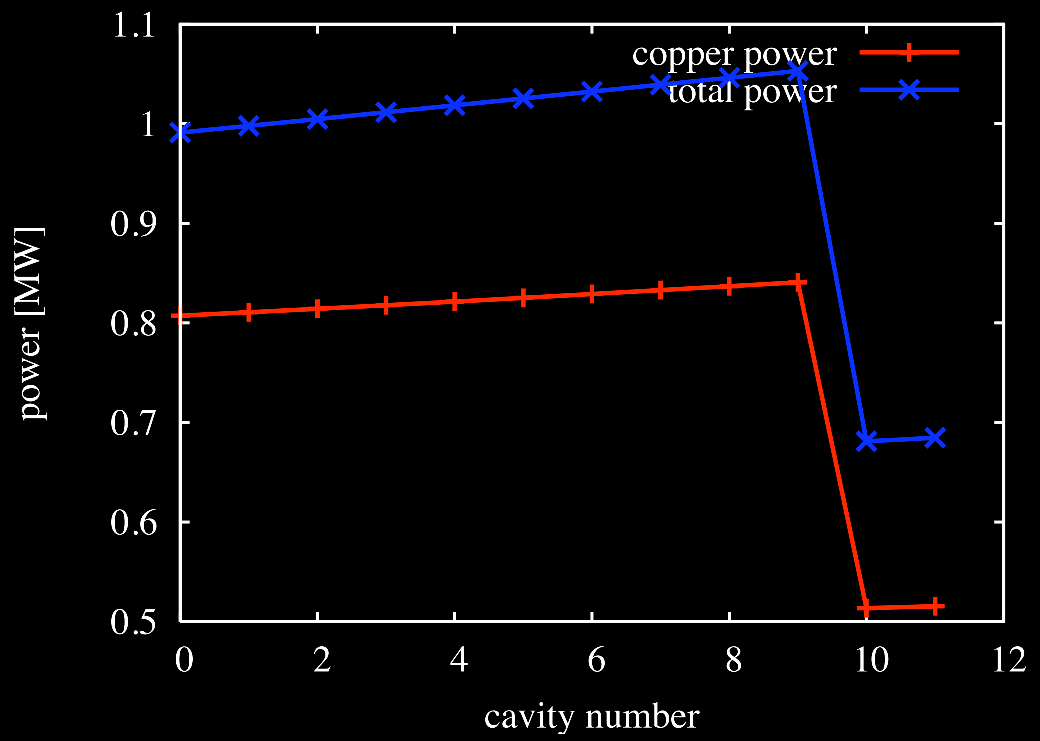


filling time at nominal gradient (3.25-4 MV/m): 18 μs

Cavity filling assuming full klystron power (1.3 MW), pessimistic estimate

power splitting from one klystron to 2 cavities

- neither the controls people like it, nor the RF power guys,
- a problem that needs to be solved for the CCDTL as well, once we upgrade from LEP klystrons (1.3 MW) to new high-power klystrons (2.5 MW),
- power consumption and beam loading of neighbouring cavities is basically identical,



many thanks to:

P. Bourquin, Y. Cuvet, G. Favre, R. Folch, J.-M. Geisser, G. Geschonke, D. Glaude, T. Kurtika, J.-M. Lacroix, A. Lombardi, E. Page, C. Saint-Jal, E. Sargsyan, S. Sgobba, T. Tardy, M. Timmins, G. Vandoni, M. Vretenar, ...

Summary I

- the SCL has been replaced with the PIMS,
- only one frequency: 352.2 MHz,
- same length, slightly lower cost:
    - the mechanical design was simplified,
    - the tuning and commissioning effort was considerably reduced,
    - no additional cavities are needed for energy modulation,
    - construction and long operational experience (LEP until 2000) available at CERN
    - less money manpower is needed to make it work!

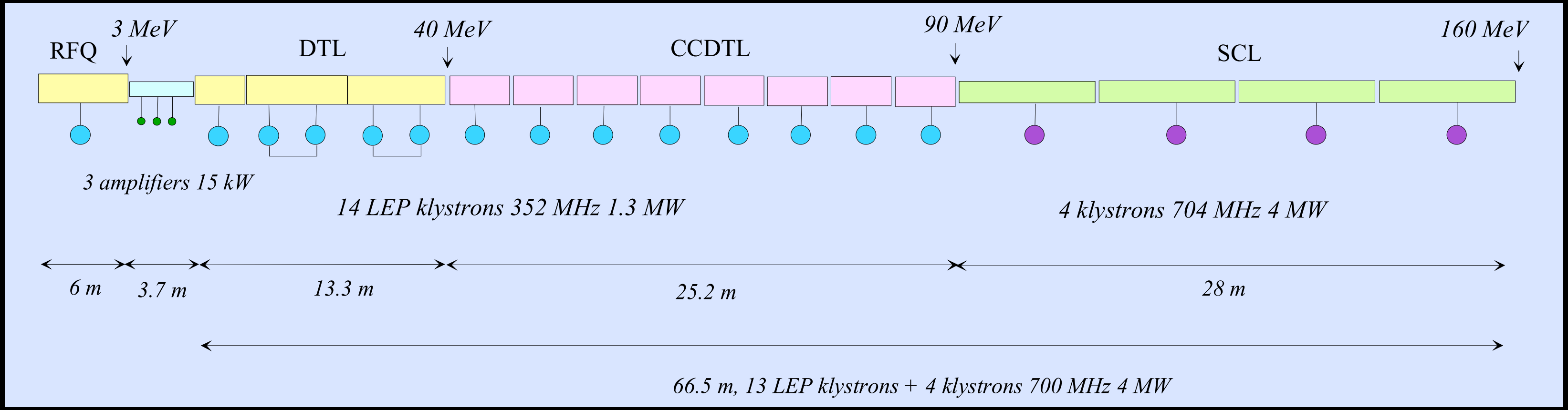
Summary II

- dynamic behaviour of PIMS has been analysed to much more detail than for LEP / or for the original solution of the SCL,
- transient effects are smaller than the errors coming from klystrons and modulators, and their duration is shorter,
- for π-mode and π/2-mode transient effects are limited to the transients: in NC structures this means 10 - 20 μs (SC structures: ~0.5 ms), any potential beam disturbance during the transients is removed in the head dump before injecting into the PSB,

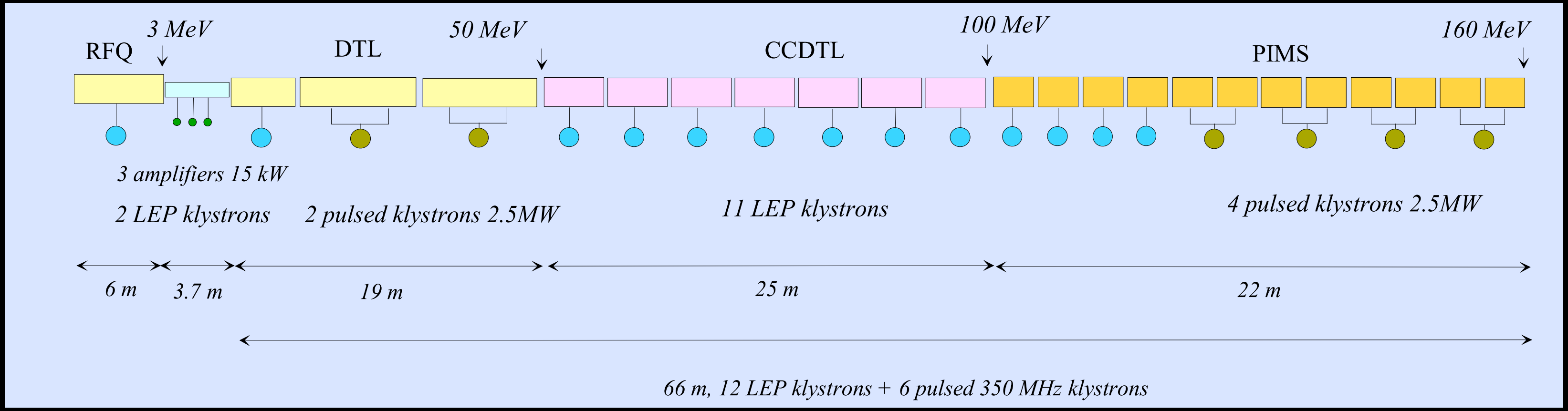
extra slides

RF system II: frequency

12/2006: 14 LEP klystrons (**352.2 MHz**, 1.3 MW), 4 new klystrons (**704 MHz**, 4 MW), 18 in total



09/2007: 13 LEP klystrons (**352.2 MHz**, 1.3 MW), 6 new klystrons (**352 MHz**, 2.5 MW), 19 in total



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RF cavities: Summary new(old)

	RFQ	DTL	CCDTL	PIMS (SCL)
E_{out} [MeV]	3	50 (40)	102 (92)	160
No. cavities	1	3 (3)	7 (7)	12 (20)
E_{acc} [MV/m]	-	3.2 (3.3 - 3.5)	3.9 - 3.1 (3.9 - 2.8)	4.0 - 3.9 (4.0)
Max. field [kilpatrick]	1.7	1.6 (1.7)	1.7	1.8 (1.2)
RF power	0.54 (1.0)	4.7 (3.9)	7.0 (6.4)	11.9 (12.5)
No. klystrons	1	1+2 (5)	7 (8)	4+4 (4)
Length [m]	3.0 (6.0)	18.7 (13.4)	24.3 (25.2)	21.5 (28.0)

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e-beam welding at CERN

Cost estimate from TS/MME:

	prototype	12 cavities
tooling & preparation	115.0 kCHF	18.6 kCHF
e-beam welding	11.3 kCHF	135.8 kCHF
total cost	126.3 kCHF	154.4 kCHF

The high initial cost of tooling suggests that: if we build a prototype at CERN, then either to weld all structures at CERN or to transfer the tooling to industry.