RF and Feedback Developments at the ESRF

G. Gautier, N. Guillotin, J. Jacob, J.-M. Koch, J.-M. Mercier, G. Naylor, E. Plouviez, J.-L. Revol, V. Serrière

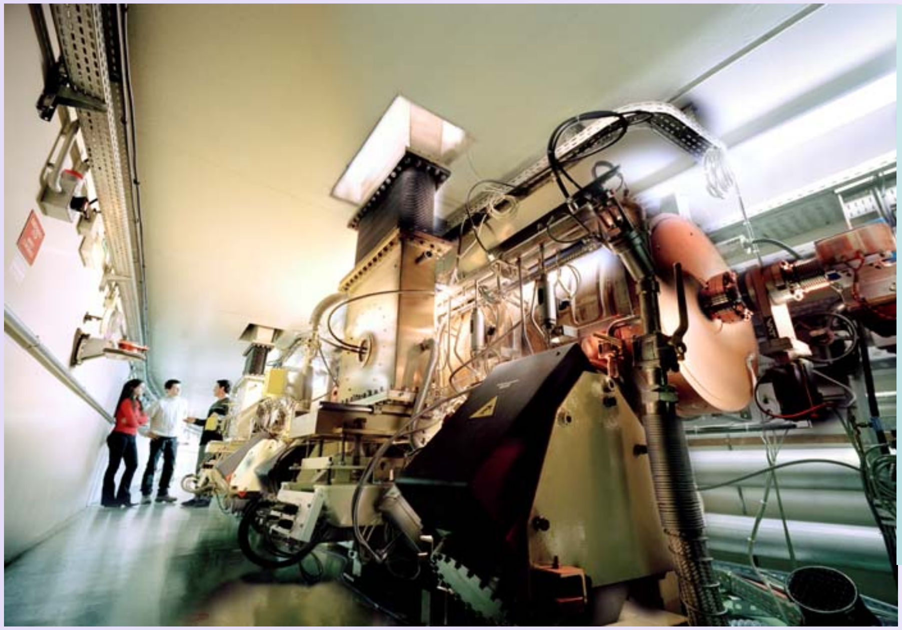
ESRF

Thanks also to many other colleagues at the ESRF

Three-Way Meeting 2008

APS – Argonne National Laboratory, March 14 – 17, 2008

Existing 352.2 MHz RF system



6 five-cell cavities on the storage ring

R/Q = 139 Ω / cell *Qo = 38500*

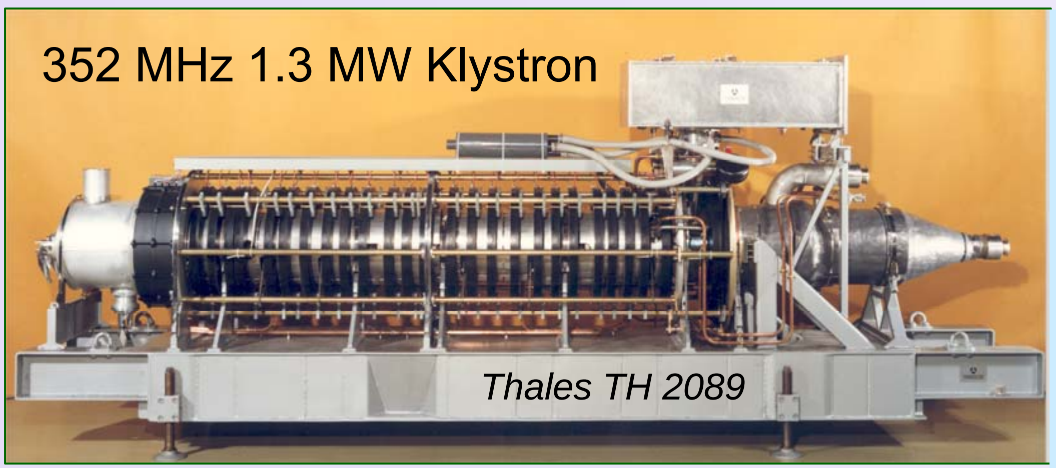
Rs = 26.8 MΩ (5 cells) f_{rf} *= 352.2 MHz*

V_{nom} *= 1.4 … 2.5 MV*

2 couplers: β_{max} *= 4.4*

Max 170 kW / coupler

☞ *Undamped HOM*



- 2 out of 3 installed klystrons needed to feed the 6 cavities at 200 mA

⇒ 1 klystron available for the cavity power test stand or to back up operation for any bunch filling mode

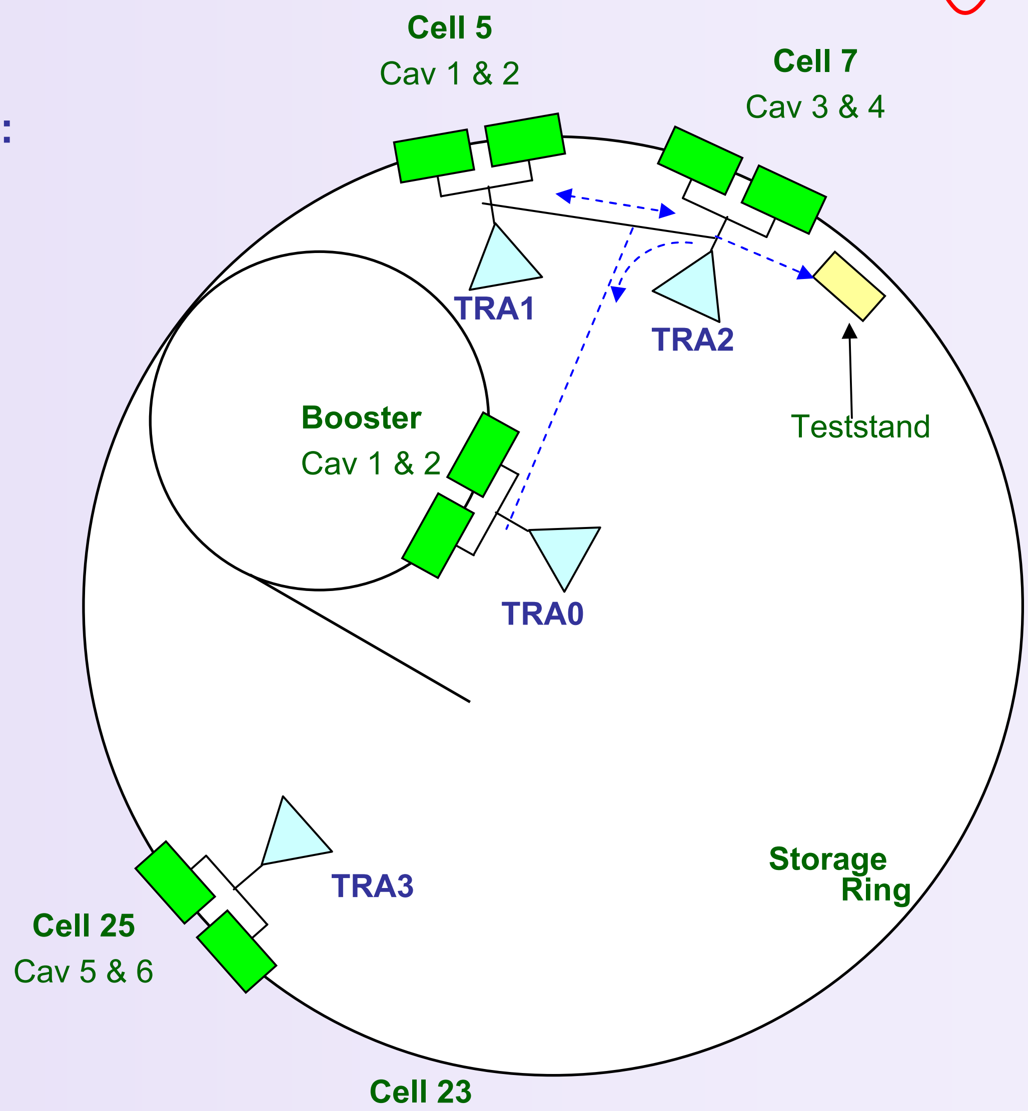
RF operation at 200 mA with safety margin

Nominal configuration at 200 mA:

- TRA0 on booster cavities 1,2
- TRA1 on SR cavities 1,2,3,4
- TRA3 on SR cavities 5,6
- TRA2:
  - available for the teststand
  - can be switched to replace TRA0 or TRA1 when they have to be shut down

200 mA in case of TRA3 fault:

- TRA1 on SR cavities 1,2
- TRA2 on SR cavities 3,4
- Cavities 5,6 not powered



Mastering instabilities at 200 mA

- TCBI – Transverse Coupled Bunch Instabilities
  - ☞ Emittance increase → loss in brilliance
    - ➢ Resistive wall instability
    - ➢ Ion trapping
    - → Mastered by an increased **chromaticity**
    - ➢ Transverse cavity HOM are masked

- LCBI – Longitudinal Coupled Bunch Instabilities
  - ☞ Energy spread → loss in brilliance, mainly for higher harmonics of undulator radiation
    - ➢ Instabilities driven by longitudinal **HOM from 6 five-cell Cu cavities** for I_{beam} > 50 … 130 mA, depending on T_{cav}
    - → Stabilisation by **Landau damping** thanks to transient beam loading from non-symmetric **fractional filling → 200 mA in 1/3 et 2/3 filling**
    - → 1998: Improved **Cavity temperature regulation $T_{cav} = T_{set} \pm 0.05^{o}C$,** for a precise control of the HOM frequencies
      - ⇒ Stable beam at **200 mA** in **uniform** and symmetrical 2 x 1/3 filling

Further Current Upgrade

- 300 mA
  - Achieved in Machine Physics test in December 2006
  - Foreseen in USM after tests with individual beam lines in 2008/2009

- 500 mA
  - Not scheduled for the coming accelerator upgrade
  - Subject to R&D for the coming 10 years, in preparation of a possible later upgrade
  - Any new RF design will have to be compatible with a possible increase to 500 mA

Increase to 300 mA

- ✓ No intrinsic limitation: neither in RF power, nor from thermal or radiation load
- ➢ However, since 2003 unsuccessful search for a stable working point
  - → HOM driven LCBI above 200 … 250 mA for any T_{cav}

⇒ **End of 2004: Decision to implement a digital bunch-by-bunch feedback system** (already reported at last 3 WM in June 2006)

- ➢ LFB (Longitudinal Feedback): to damp HOM driven LCBI
- ➢ TFB (Transverse Feedback): allows operation at zero chromaticity and to damp ion instability at 300 mA
- ➢ Goal: **deliver 300 mA to users** for limited periods of time in 2008 / 2009

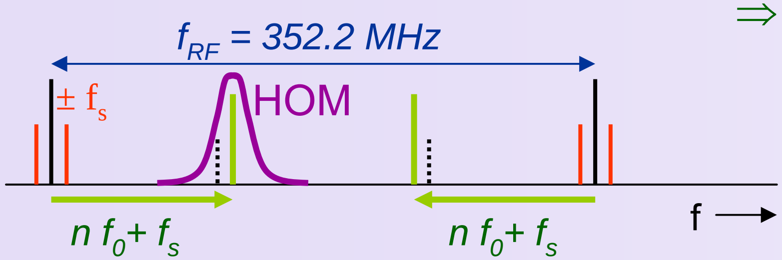
→ December 2006: 300 mA of stable beam successfully stored during machine physics shifts thanks to LFB

Part I

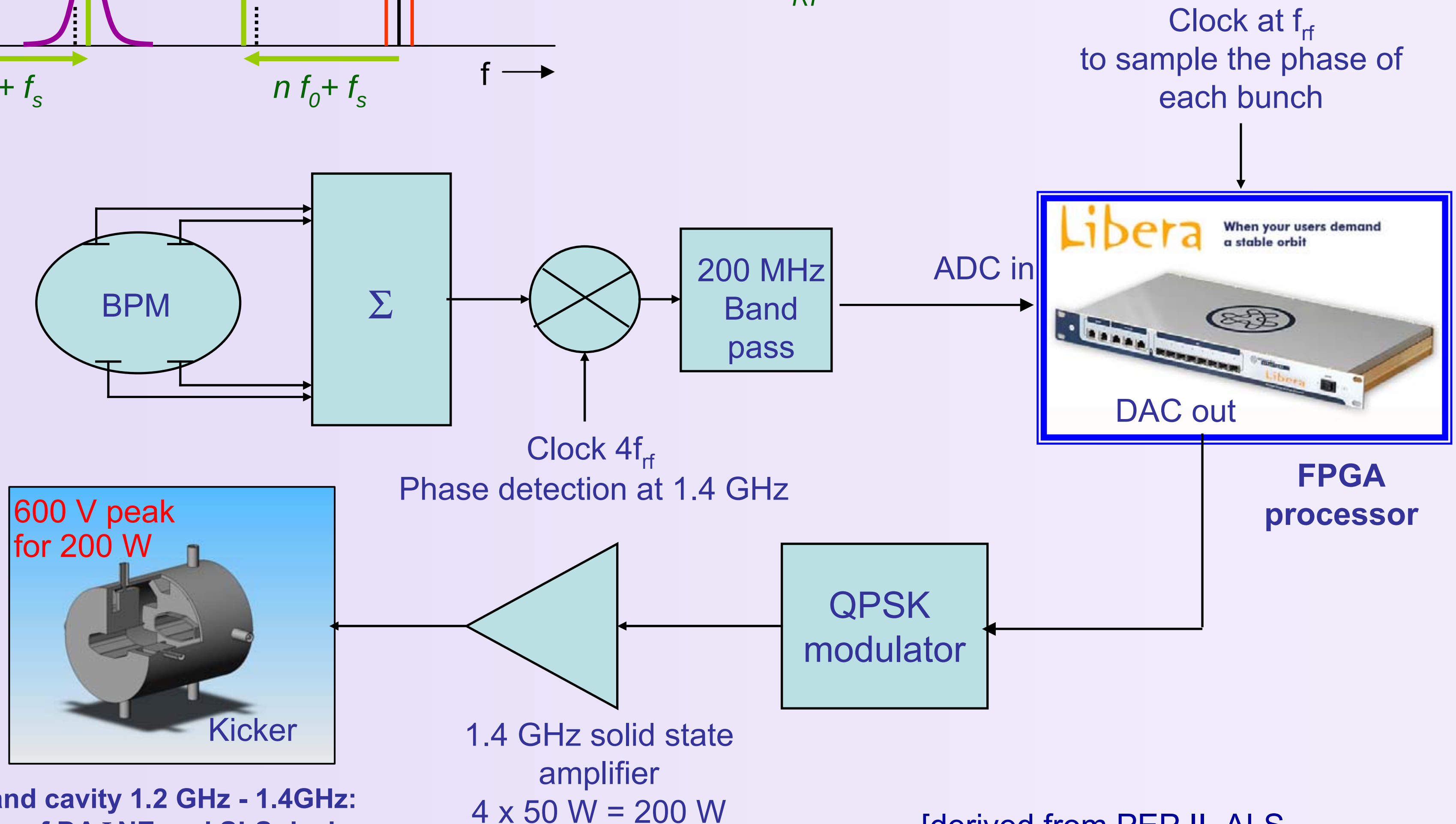
Bunch-by-Bunch Digital Feedback Systems

1. LFB
2. TFB

Longitudinal Feedback - LFB



⇒ Detection of all possible coupled bunch modes within bandwidth: $f_{RF}/2$ = 176 MHz



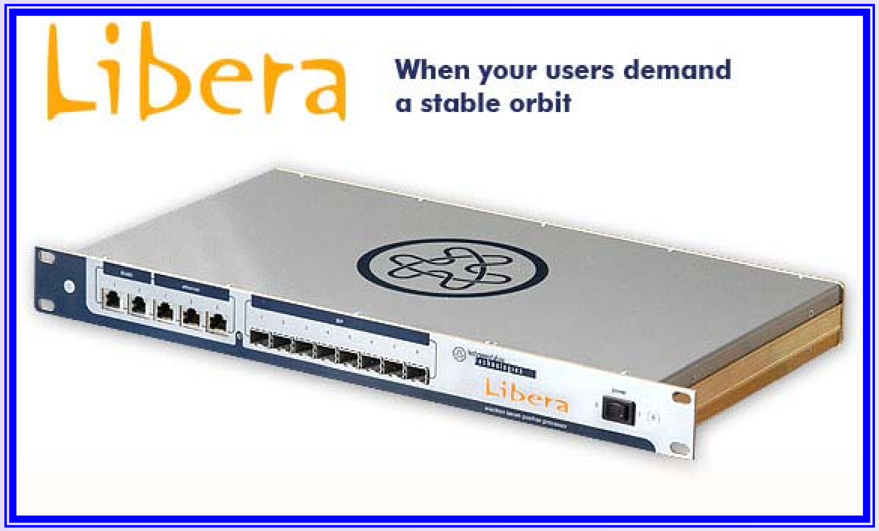
Broad band cavity 1.2 GHz - 1.4GHz:
Adaptation of DAΦNE and SLS design
to ESRF frequencies ESRF

[derived from PEP II, ALS, DAΦNE, SLS systems …]

LFB figures

- Highly sensitive bunch phase measurement
  - ➢ 1 fs/turn
  - ⇒ minimum feedback kick: 4.7 V, well within 600 V kicker spec
- 14 bit ADC: $\Delta\tau_{max} = \pm 8$ ps
- Efficient pre-filtering of spurious signals not related to the unstable synchrotron oscillations:
  - ➢ Mode 0 oscillation, beam loading phase transients, injected beam oscillation…
- ESRF naturel longitudinal damping time
  - ➢ $\tau_s = 3.6$ ms
- Phase measurement requires a numerical differentiation to compute proper voltage kick: FIR centered on $f_s \Rightarrow$ limits active damping time:
  - ➢ $\tau_{LFB} = 0.5$ ms $\approx \tau_s / 7$
  - ⇒ Allowed to store 300 mA, but **Combination** of HOM control by Cavity Temperature regulation and LFB damping required !

FPGA – digital signal processor



Bunch by bunch feedback:

- parallel processing of all 992 bunches
- processes shifted by $T_{rf} = 2.84\ ns$
- Each process sequenced at $T_0 = 2.8\ \mu s$

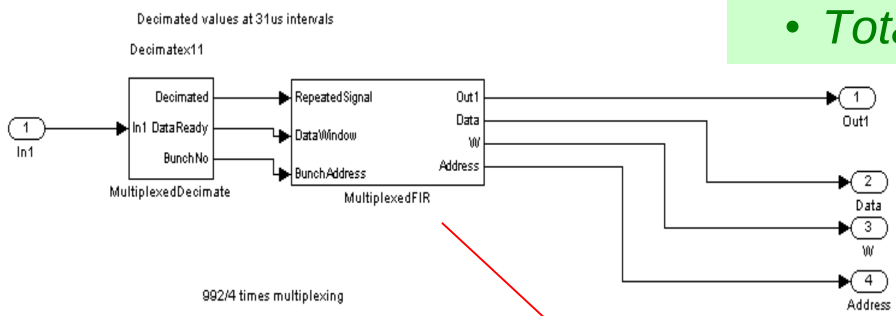
Virtex-II from Xilinx

- 100 Gops
- Code development with System Generator (Xilinx / The MathWorks)
- Data transfer in and out:
- Four 14 bit ADC channels 4 x 88 MHz
- One 14 bit DAC (DDR) at 352 MS/s
- Fast DDR2 RAM – 64 MB

FPGA – Filter block: decimation + FIR + mode 0 removal

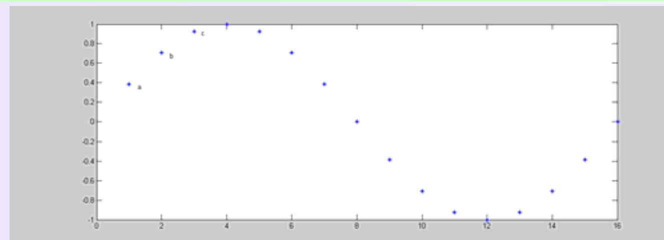
Factor 11 decimation:

$11\ T_0 = 31\ \mu s$

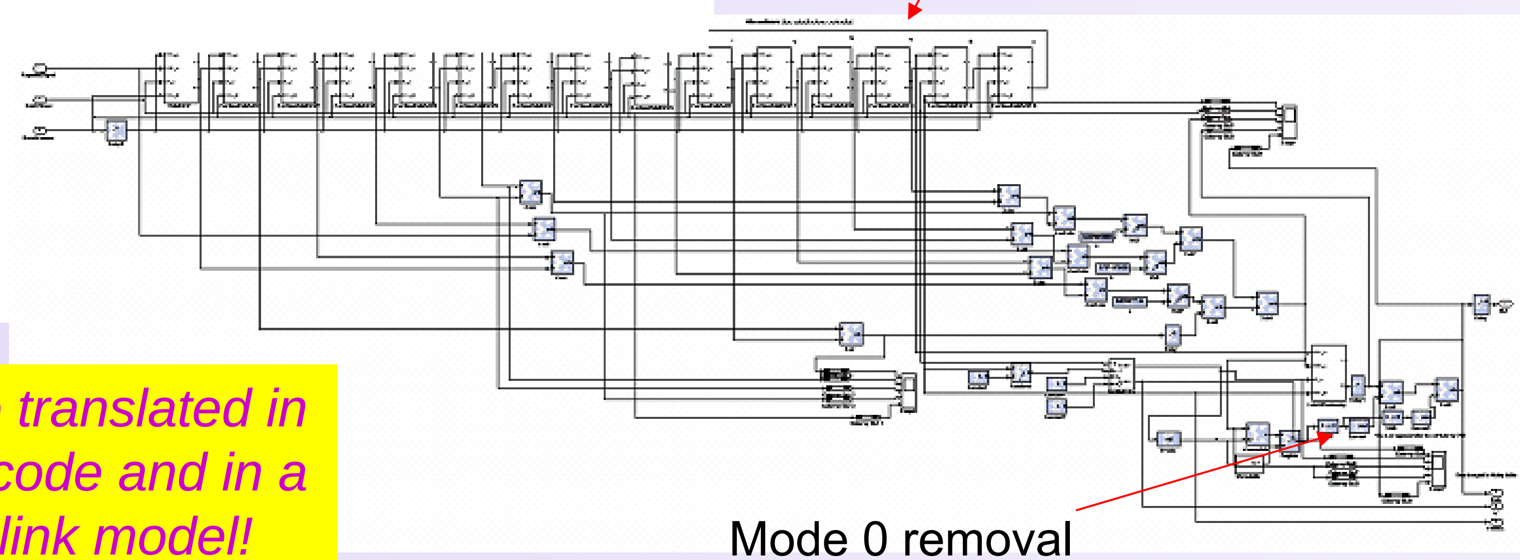


16 TAP FIR: *16 x 31 μs = 0.5 ms = $T_{synchrotron}$*

- *BP filter at f_s*
- *Differentiation ($V_{kick} \sim j\tau$): phase shift by 90°*
- *Total averaging 176, sensitivity: 1fs -> 0.08 fs*



FIR: (a,b,c,1,c,b,a,0,-a,-b,-c,-1,-c,-b,-a,0)

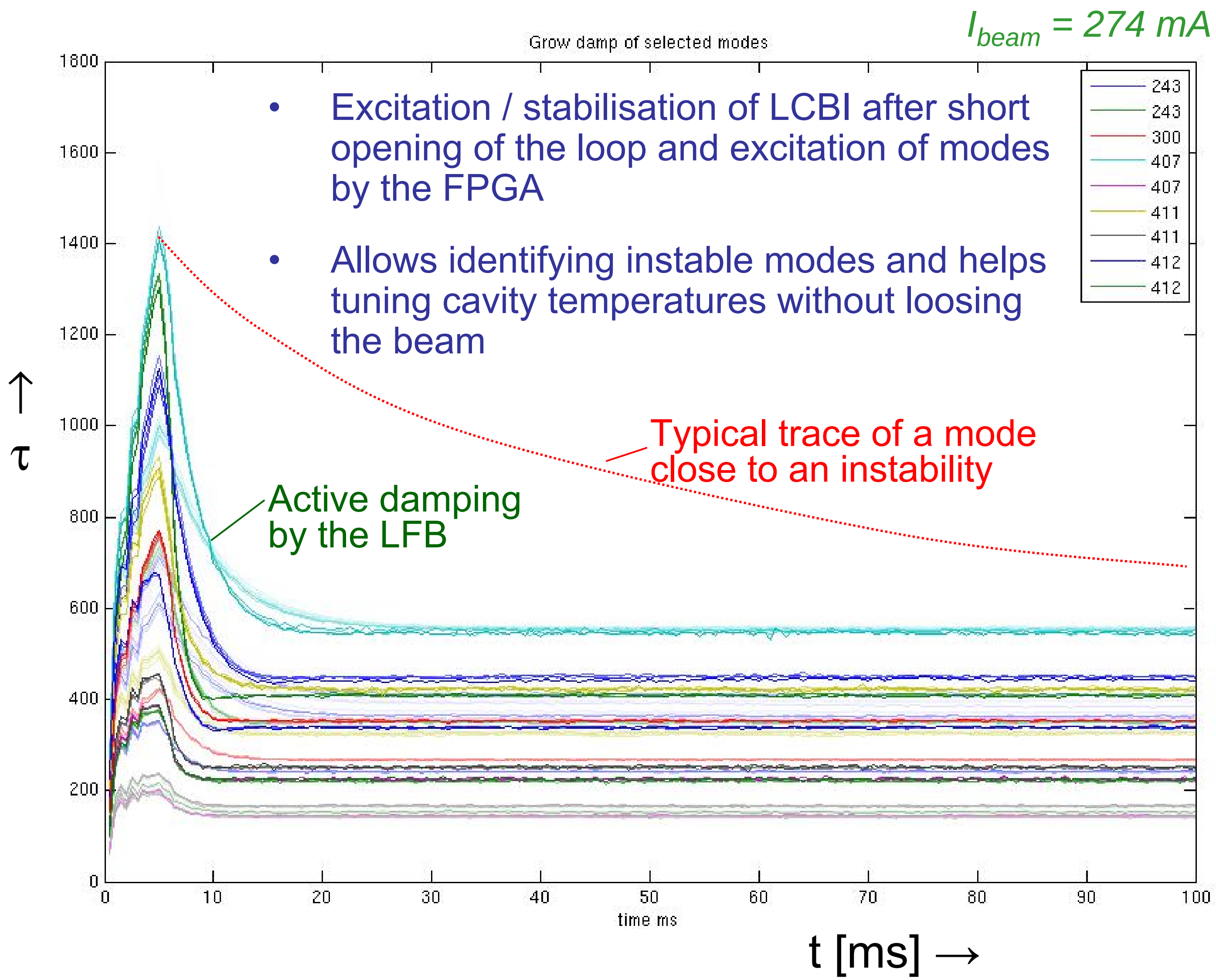


Mode 0 removal

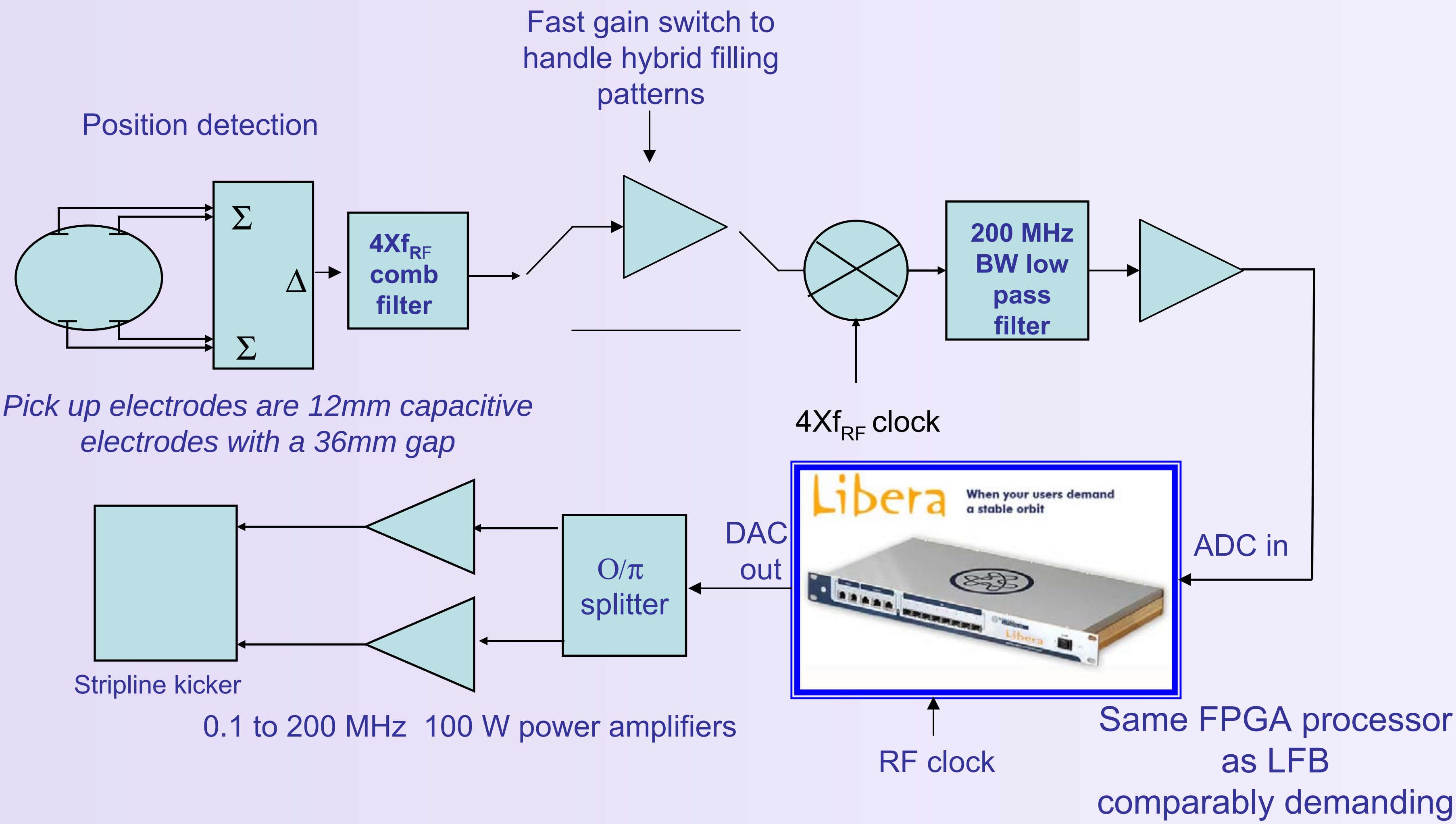
Can be translated in VHDL code and in a simulink model!

LFB: Grow-Damp measurements to tune HOM

- Excitation / stabilisation of LCBI after short opening of the loop and excitation of modes by the FPGA
- Allows identifying instable modes and helps tuning cavity temperatures without loosing the beam

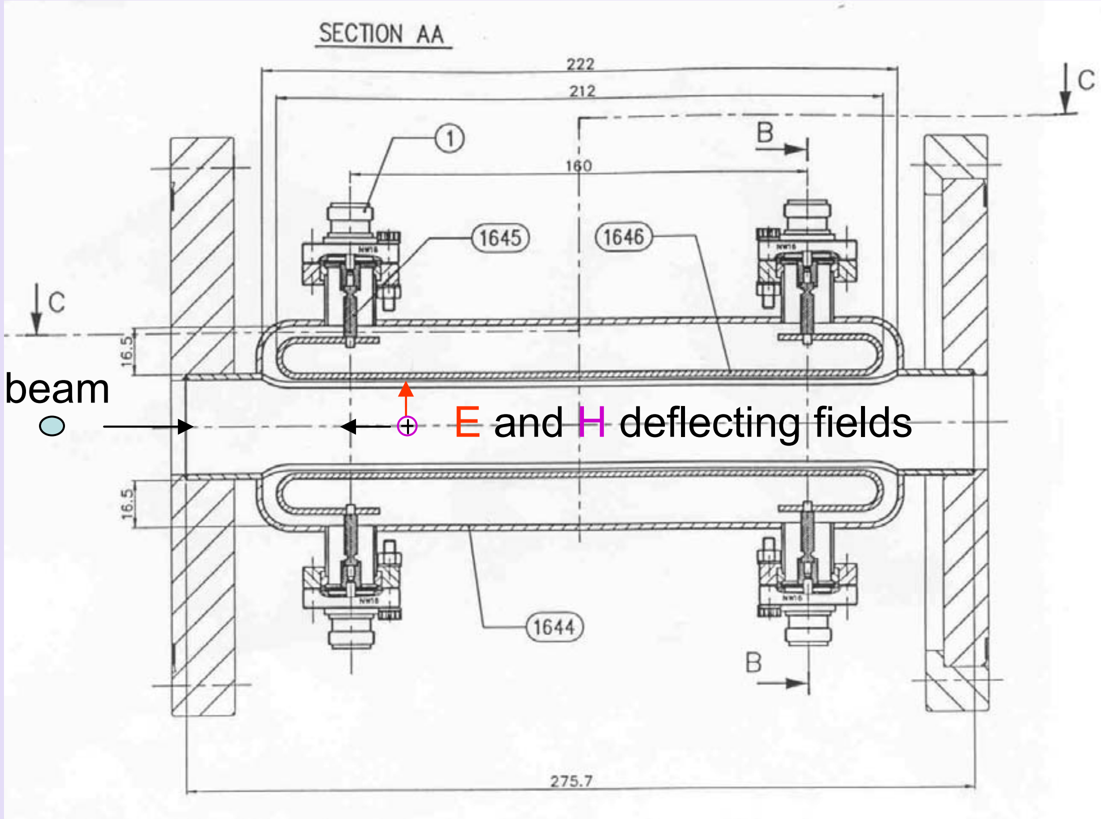


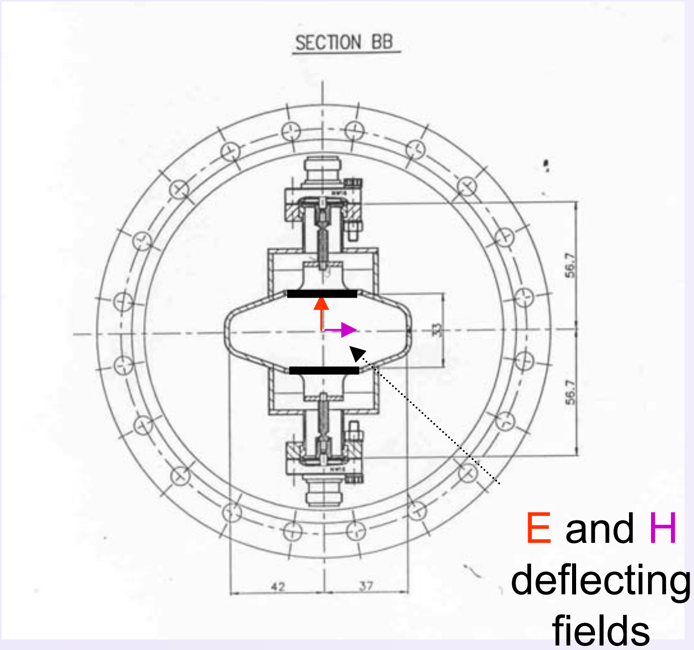
Transverse feedback - TFB



Detection of the pick up signals with a 4xf$_{RF}$ clock improves the resolution

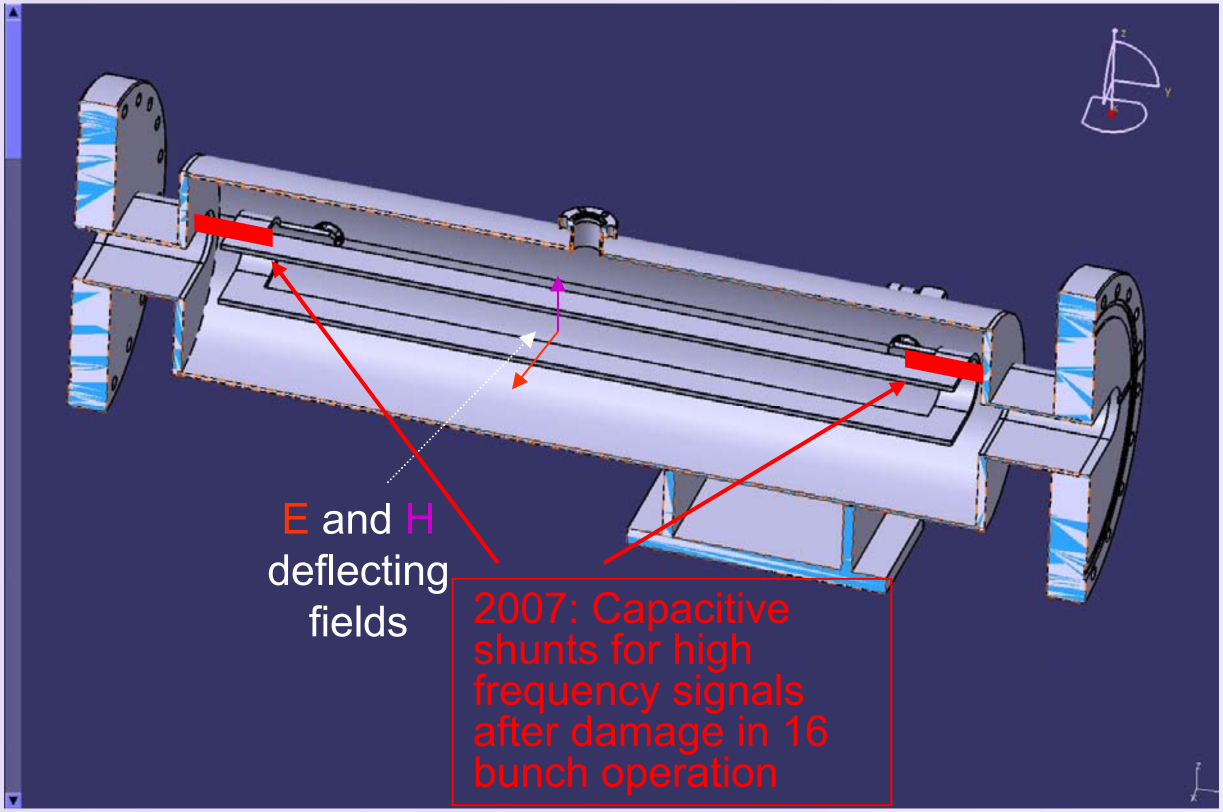
Vertical kicker layout





- Kicker design: relatively straightforward but HV issues in 4x10mA filling...
- Vertical kicker strength: low (typical cleaning with a 25V/cm field)
- Position measurement resolution demanding; 4µm over 200 MHz of bandwidth required to preserve 20 pm vertical emittance

Horizontal kicker layout



Half view:
- Stripline
- U shape to increase the shunt impedance

- Horizontal kicker strength: demanding due to the large spurious kick of the injection (1.5 mm for β=36m); it will limit the damping time.
- Signal processing : processing speed and power similar to the longitudinal case.

TFB figures

- Turn by turn resolution:

  4μm at .2mA/bunch (200mA)

- Loop filter:

  Vertical: 8 taps FIR, 3 SR revolution periods

  Horizontal:7 taps FIR, 3 SR revolution periods

  Simplest shape: sine shape, no windowing

- Damping time:

  Vertical system: 20 turns (50 μs)

  limited by the algorithm latency, still 20 dB gain margin

  Horizontal system: 100 turns (280 μs)

  limited by the ratio between the single turn kick amplitude and the amplitude of the injection oscillation due to the kicker bump imperfect closure.

TFB - some results

- Damping of resistive wall instability
  - 200 mA with $\xi_x = 0$ and $\xi_z = 0$

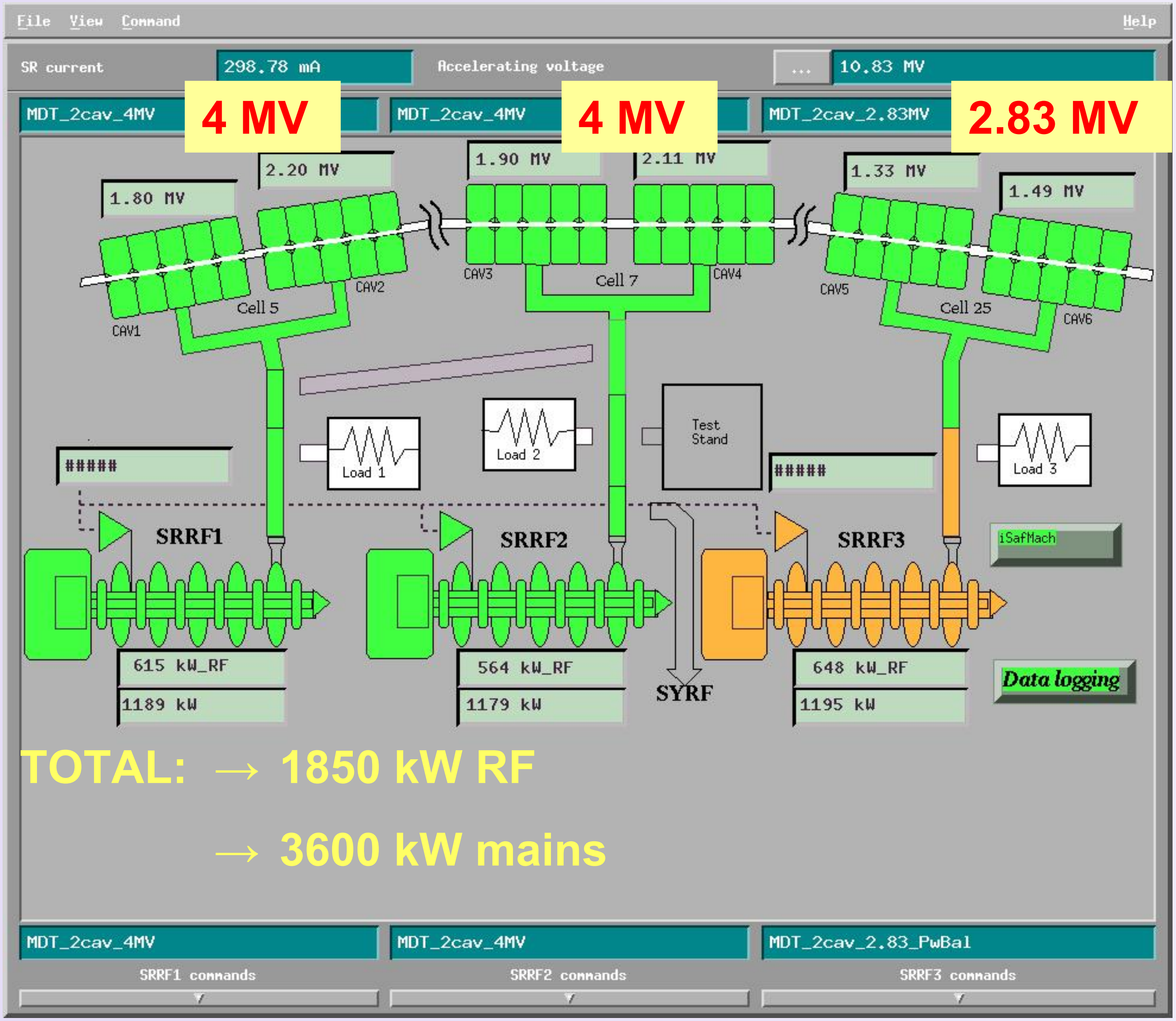
- TFB_z against vertical blow up due to ion trapping in uniform fill
  - At 300 mA:
    - ◊ TFB_z = OFF: ion trapping → vertical blow up → after 20 min beam loss
    - ◊ TFB_z = ON: vertical blow up limited to $\varepsilon_z = 80$ pm
  - At 200 mA in USM:
    - ◊ ε_z : 35 → 25 pm, applied since mid 2007

- At given chromaticity: Increase of single bunch head tail instability thresholds by a factor 2.5 to 3

Part II

ESRF RF upgrade for the coming decade

Summary / tests with 300 mA at ESRF



RF:

- 11 MV necessary for Robinson stability
- All 3 transmitters in operation ⇒ no margin for test stand or in case of equipment failure

LFB:

- Stabilisation of HOM up to 300 mA

TFB vertical

- Needed to control beam blow up due to ion trapping

Existing system

- At 300 mA: all SR transmitters are needed
  - TRA1 → Cavities 1 & 2
  - TRA2 → Cavities 3 & 4
  - TRA3 → Cavities 5 & 6

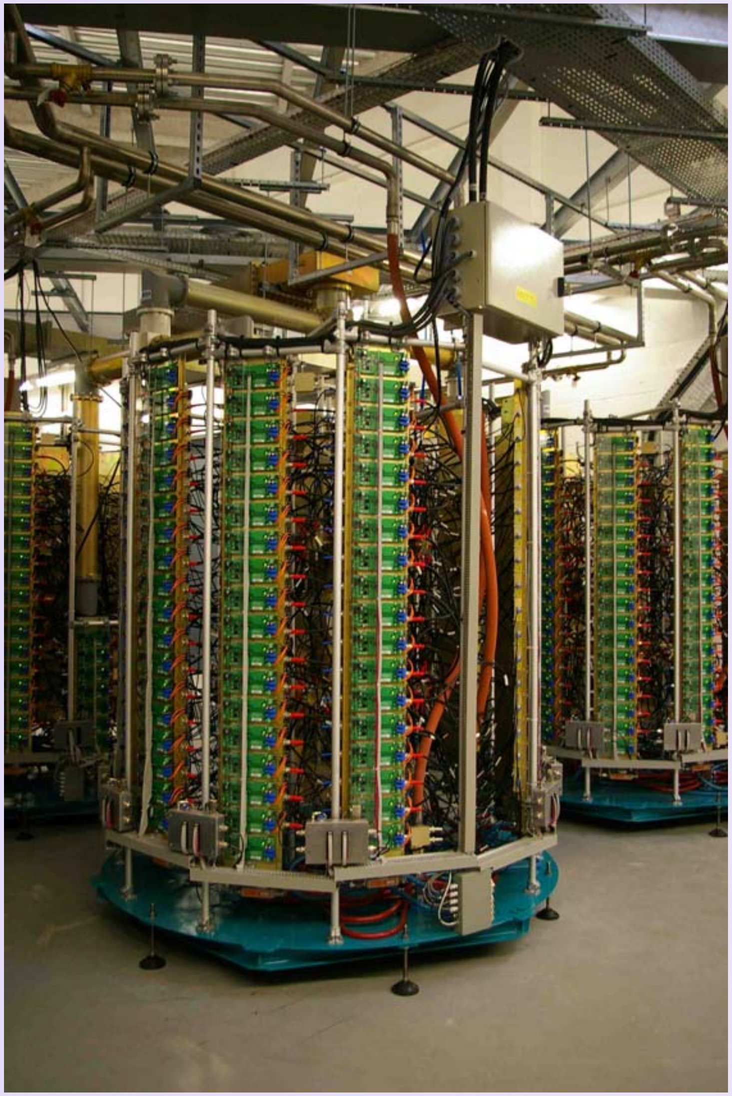
  ⇒ No spare transmitter = no safety margin

- Re-establishing a safety margin at 300 mA would require 2 more 1.3 MW transmitters:
  - → One to back up TRA0 (booster), TRA1 and TRA2 (SR)
  - → One to back up TRA3 (SR)

Transmitter upgrade

- Existing RF transmitters:
  - Only one klystron supplier left
  - These klystrons are particularly subject to instabilities: none is presently in operation at ESRF
- Proposed upgrade with Solid State Amplifiers (SSA):
  - Replace klystron transmitters with SSA
  - SSA highly modular $\Rightarrow$ redundant $\Rightarrow$ intrinsically reliable
  - Good experience at SOLEIL, yet still R&D to find even better transistors
  - 20 dB less phase noise
  - No HV
  - No X rays
  - Easy maintenance
  - Likely to become the new standard for high power CW RF applications

Solid State Amplifiers at SOLEIL



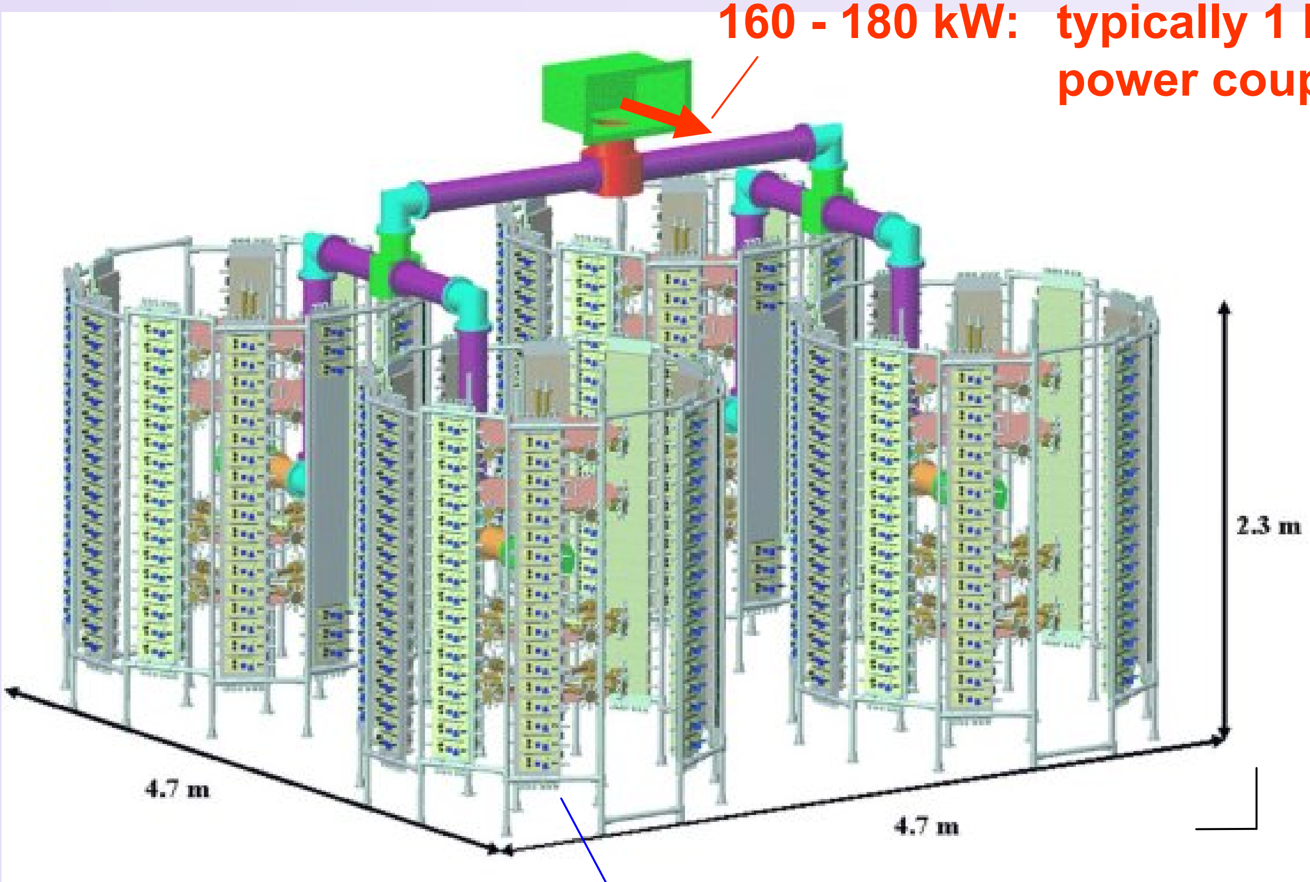
← 50 kW tower:
- tested at 45 kW
- normally operated up to 40 kW

↓ 8 towers operated at 2 x [150 to 160 kW]

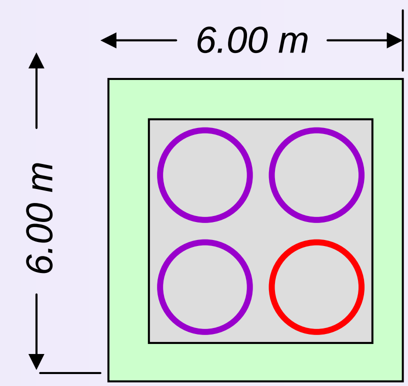
Photos: Courtesy SOLEIL

Solid State Amplifiers at SOLEIL

160 - 180 kW: typically 1 RF power coupler



1 tower = 45 kW



R&D for better transistors

- GOAL: raise the operation power from 40 to 45 kW/tower
  - SOLEIL booster: SEMELAB transistors VDMOS D1029UK05
  - SOLEIL SR: Improved performance with POLYFET LDMOS LR301 (V4)
  - Prototype tests at SOLEIL with BLF 369 from NXP:
    - ◊ Very robust device
    - ◊ Draw back: larger capacitances require larger compensating capacitors operated at high temperature, solutions under development at SOLEIL
    - ◊ BLF 369 is presently the best candidate for an ESRF amplifier
  - New BLF 574 from NXP: first samples under test at SOLEIL
    - ◊ 50 V bias instead of 30 V will bring 10 % better efficiency and reduce the losses
    - ◊ Expected to be more resistant

Procurement of solid state amplifiers

- Collaboration with SOLEIL

- Some companies already interested in supplying complete SSA systems:
  - One company: possible license agreement with SOLEIL
  - Another company proposing its own design

New Cavities for the ESRF

- Optimized for high beam current
  - At least 1 coupler per cell
    (instead of existing 2 couplers / 5-cell-cavity)

    $\Rightarrow$ Single cell cavities
  - Strong HOM damping for unconditional stability at 300 mA without active HOM damping
  - Design goal including necessary margins:
    - ◊ 500 mA in terms of power
    - ◊ 1000 mA in terms of HOM damping

Single cell NC HOM damped cavity

New 352 MHz Cavities for ESRF

⇒ R&D based on BESSY design with ferrite loaded ridge waveguides for selective HOM damping

[E. Weihreter, F. Marhauser]

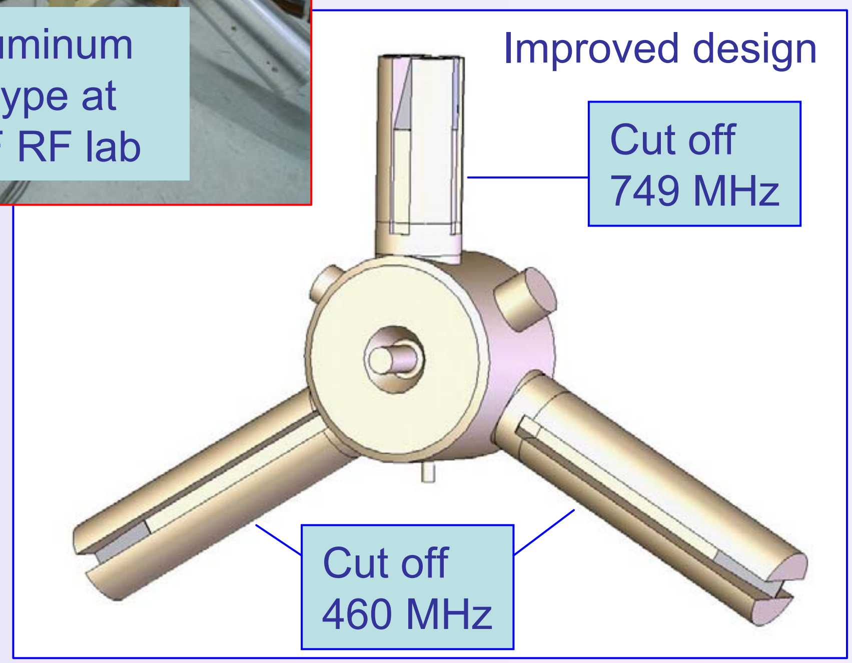
- Cavity project partly funded from the EU as work package WP13 of the ESRFUP project within the FP7 grant agreement
- Goal: produce a power prototype within 3.5 years

Qo = 30000
R/Q = 140 Ω

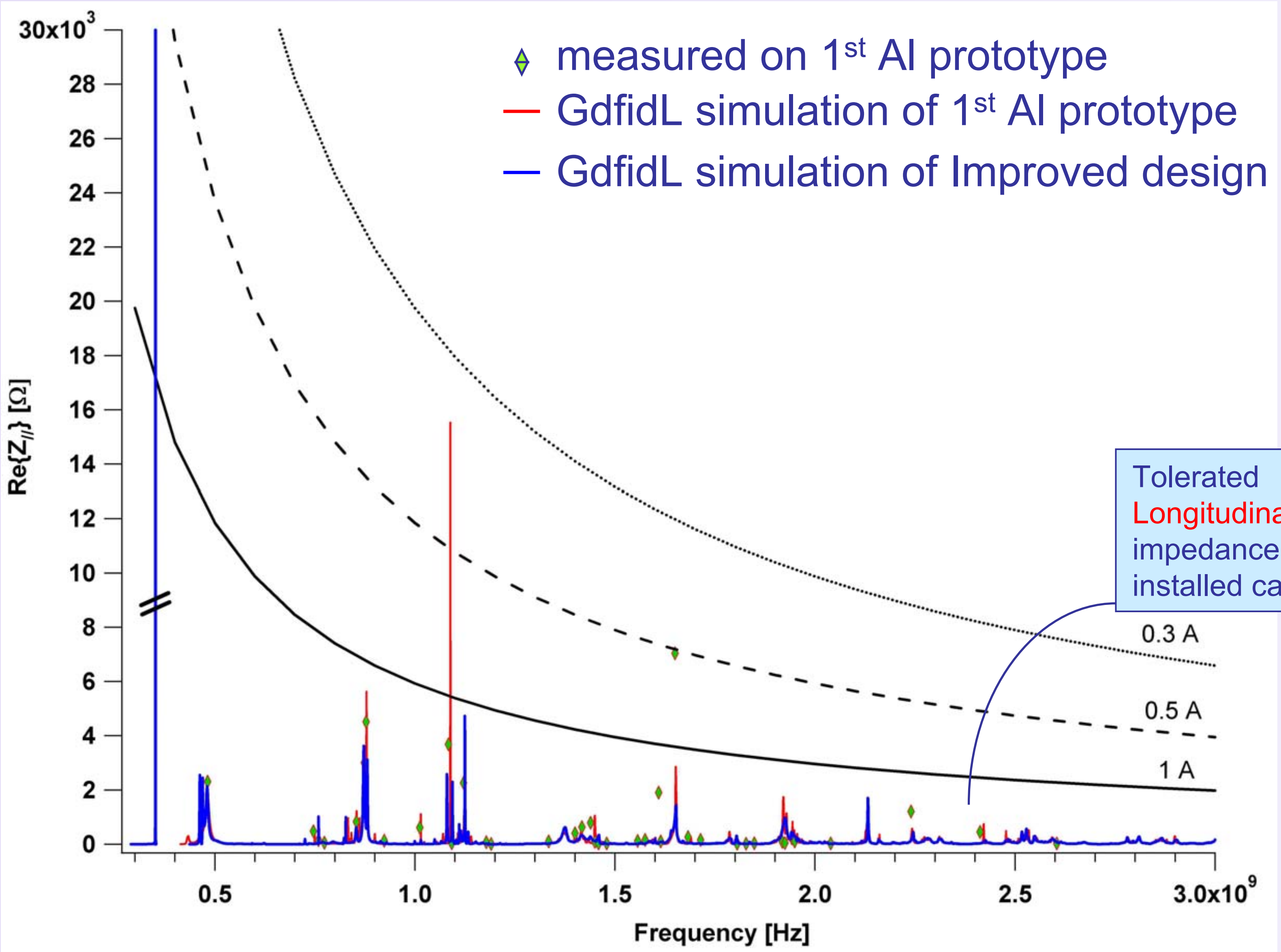
9 MV / 18 cavities:
→ P_{dissip} = 540 kW
= 30 kW/Cavity

300 mA: P_{beam} = 1.5 MW
→ P_{tot} = 114 kW / cavity

500 mA → 169 kW / cavity



Multibunch – HOM driven LCBI

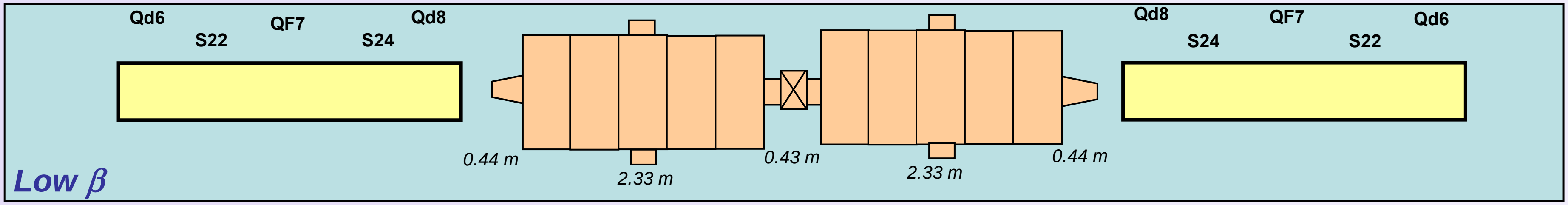


Planned RF upgrade / coming 8 years

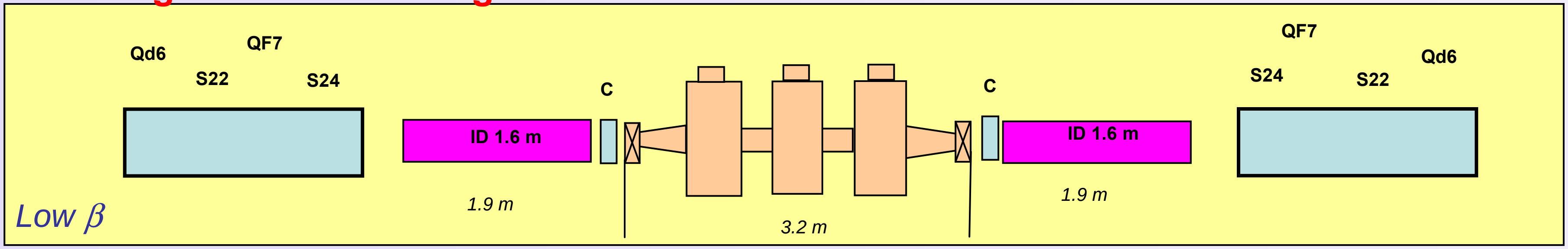
- Replacement of all 6 SR five-cell cavities with 6 x 3 new single cell HOM damped cavities
- 9 MV / 300 mA: 18 cavities at 120 kW
- 18 solid state amplifiers
  - 3 towers x 45 kW = 135 kW: sufficient margin
  - R&D for improved transistors therefore essential
  - Note that currents above 300 mA will be possible by adding a 4^{th} tower to each SR amplifier
- 4 amplifiers x 3 towers for the booster cavities
  - Can be switched ON/OFF within 10 seconds: better adapted to frequent top up operation than klystrons

Scheme for additional long beamline ID7

Present situation

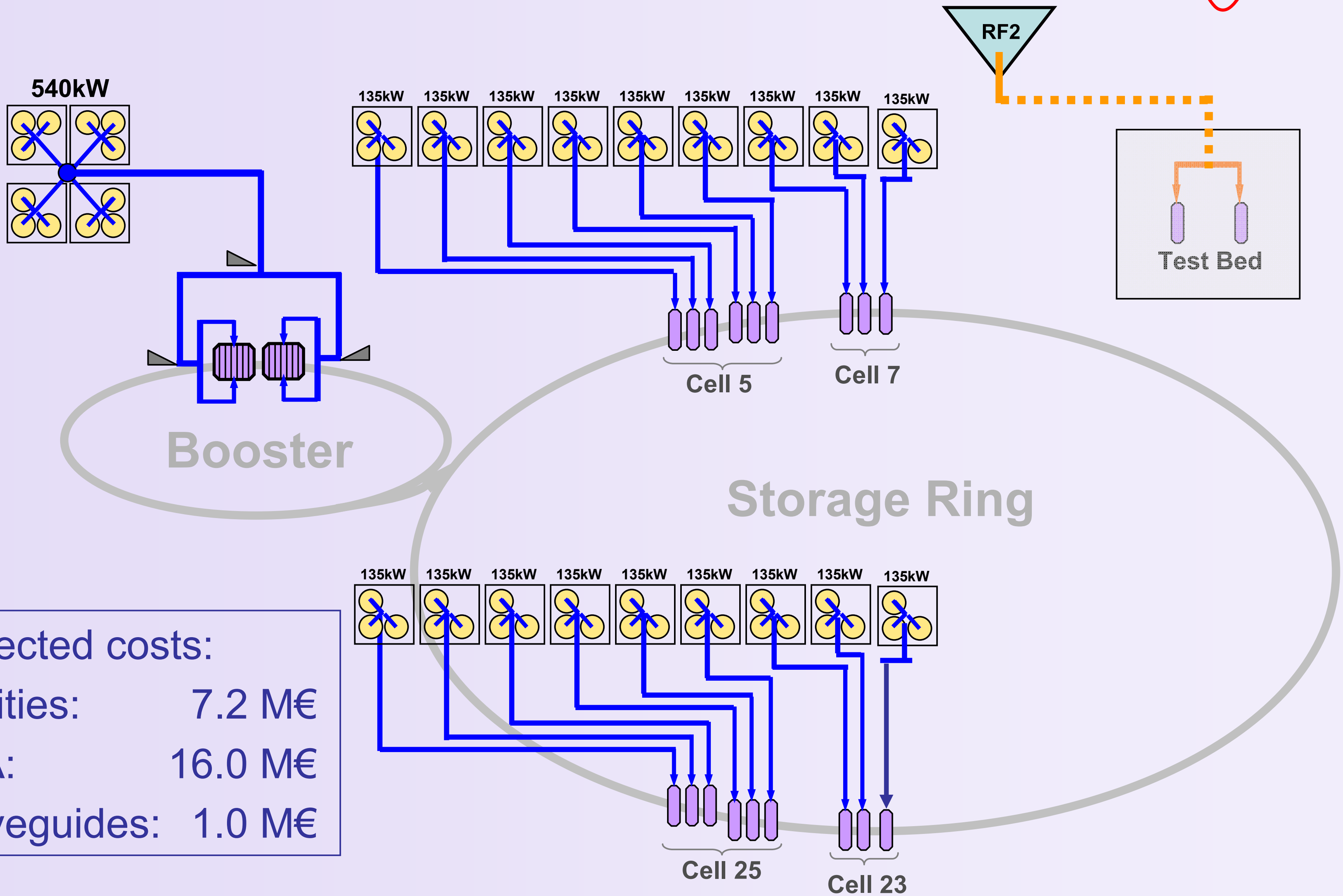


7m straight with 3 new single cell cavities



- Transform Cells 7 and 23 into long straights
- Replace SR cavity 3 with 3 single cell cavities in the middle of cell 7
  - Creates new space for a long beam line ID7 with 2 ID's
- Replace SR cavity 4 with 3 single cell cavities in the middle of cell 23
  - Keeping existing 2 canted undulators in ID23: just insert 3.2 m of RF
- Scheme could also be applied to cells 5 / 21 and cells 9 / 25

Overview RF upgrade – new cavities and SSA



Expected costs:

Cavities:	7.2 M€
SSA:	16.0 M€
Waveguides:	1.0 M€