HL-LHC & LHC Crab Cavity Planning & Summary (quickly drafted over lunch)

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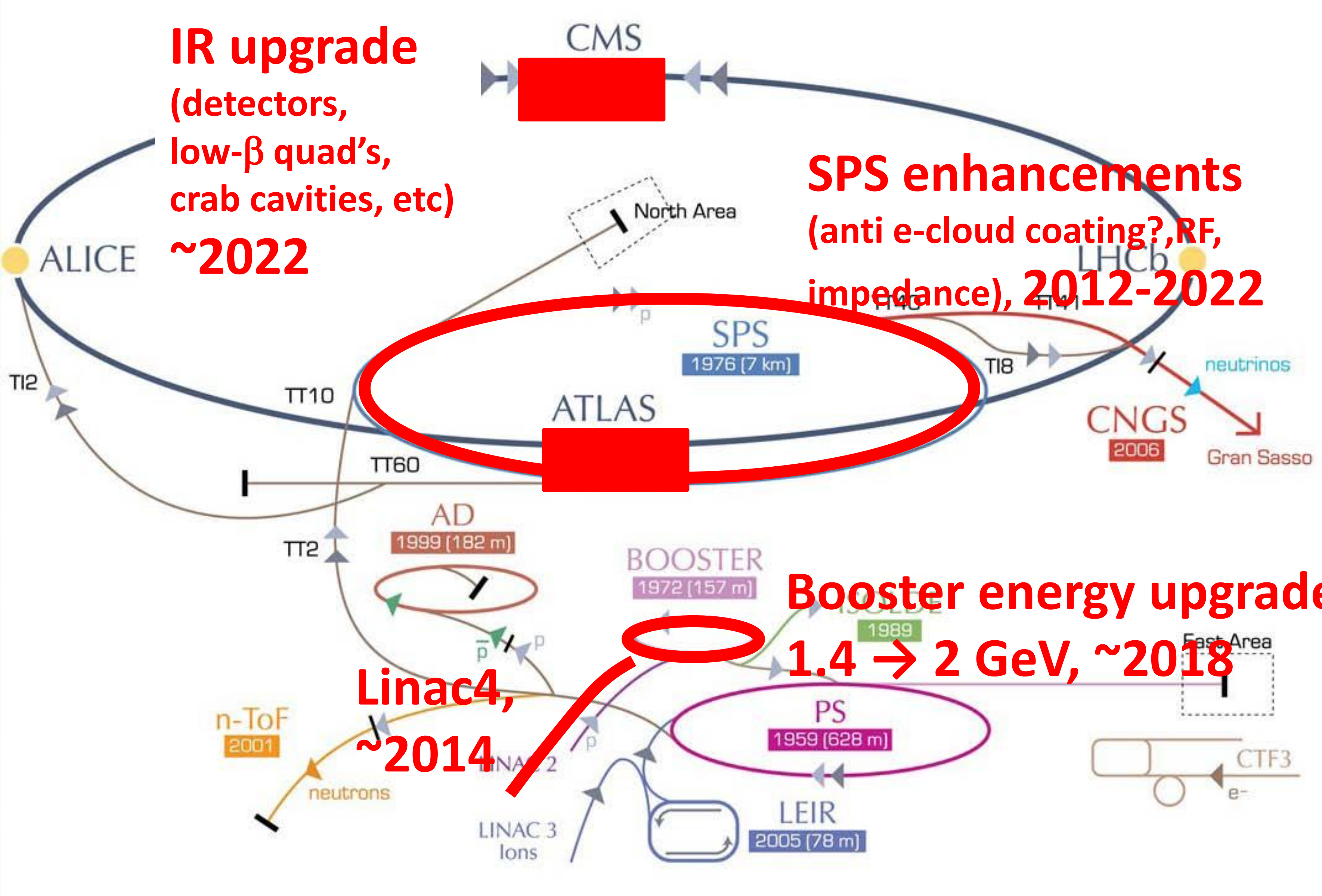
CERN

LHC-CC11, CERN, 15 Nov 2011

HL-LHC (F. Zimmermann)



LHC-CC11 agenda

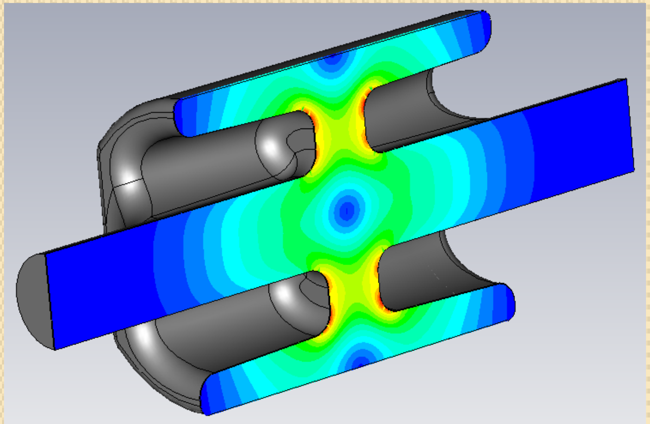
- Technology Status Review
- Revised Beam Parameters
- LHC & SPS Beam Studies

S. Yakovlev: Project-X beam splitter

- Needs 10 MV kick at 366 or 447 MHz
- Favours squashed TE113 ODU cavity – **important synergy**; identical (at least similar) cryostat?
- Difference to LHC: bunch repetition frequency (650 MHz) does not cause beam loading!
- Different flavoured problems:
  - PX Issues: microphonics, emittance dilution
  - LHC issues: beam loading, HOM damping
- RF losses not an issue – operation at 3.5 K (?)
- Planning: after 2015 (PXIE) – synergy with LHC, but less urgent.

B. Hall & G. Burt: LHC-4R

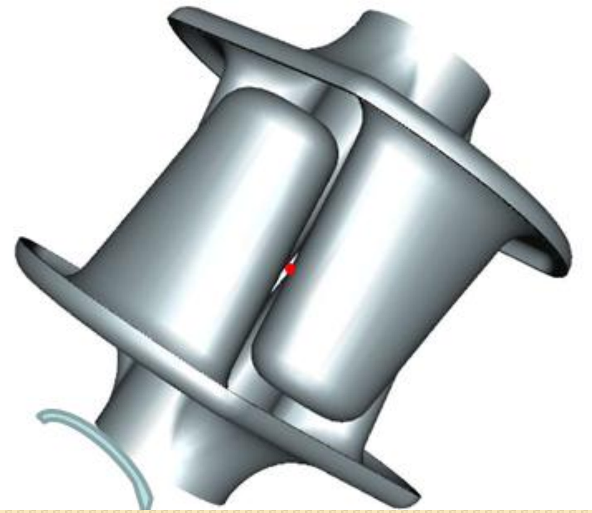
- Flattening field profile led to new shape:
- Aluminium prototype arrived:



- MP studied – OK for clean cavity, MP free after discharge cleaning (with SEY 1.25)
- Bead-pull OK,
- Couplers and HOM damper studies started.

G. Burt & R. Rimmer: 4R-LHC Possible fabrication techniques

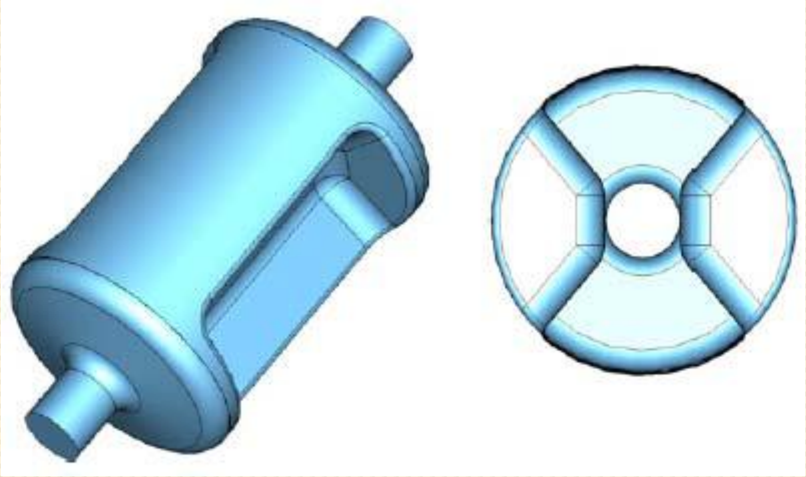
1. Nb sheets, multiple pressed sections; EBW complicated.
2. Offset rods, slanted rods to make EBW easier.
3. End plates from 1 Nb solid; Wire-etch two end-plates from 1 Nb block – modified modify shape to make compatible with EDM. ✓



4R cavity – fabrication

- Pressure sensitivity studied (Xpress): rods are quite stable, side walls buckle – could be stabilized with additional stiffeners.
- Microphonics studied: with wall thickness of above 3 mm mechanical *f* sufficiently high (above 450 Hz).
- Leak tightness: Nb block compatible? Relevant experience?

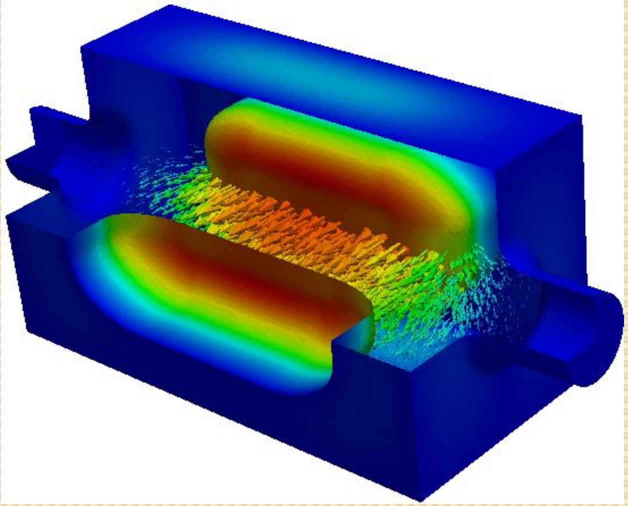
J. Delayen: ODU/JLAB Parallel-Bar I

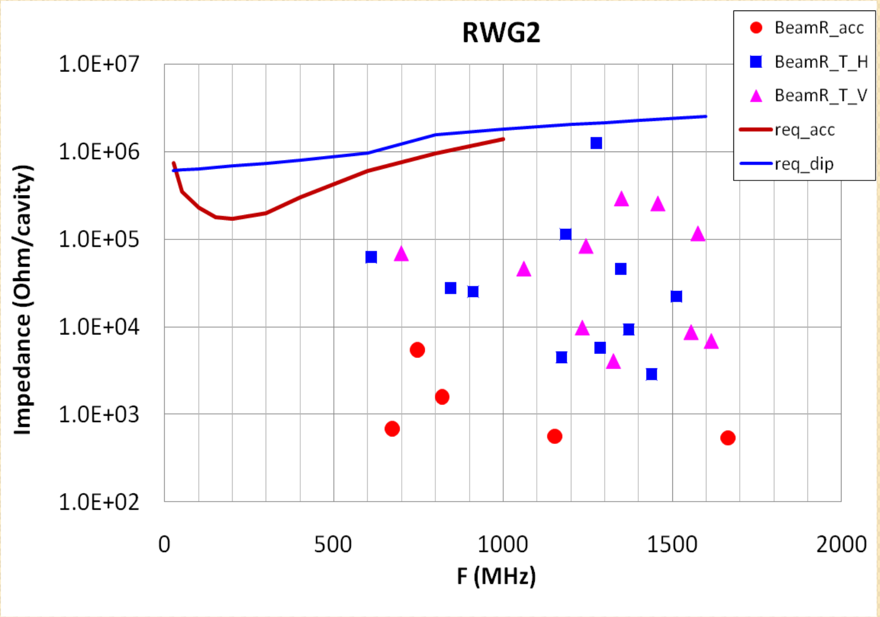


- Teamed up with SLAC (ridged waveguides)! *Excellent!*
- Synergies with:
  - JLAB 12 GeV upgrade deflecting cavity (499 MHz)
  - Project-X splitter 366 MHz
  - Electron-ion Collider (750 MHz)
- No LOM! Closest HOM > 1.5 f_0
- Evolution: rectangular to round, bent bars, ridges.
- Design optimization well advanced.
- HOM damping started
- 2 different tuner concepts being looked into.

Zenghai Li, Double-ridged cavity

- Double ridge cavity – now teamed up with ODU/JLAB. *Excellent!*
- Field flatness < 0.6% @ ± 10 mm
- first OOM far away, HOM damping relatively simple (below cut-off)

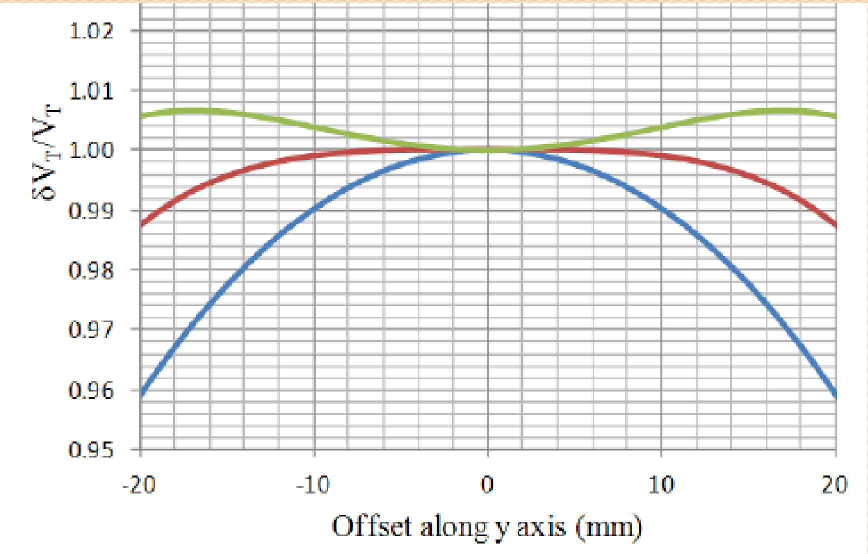


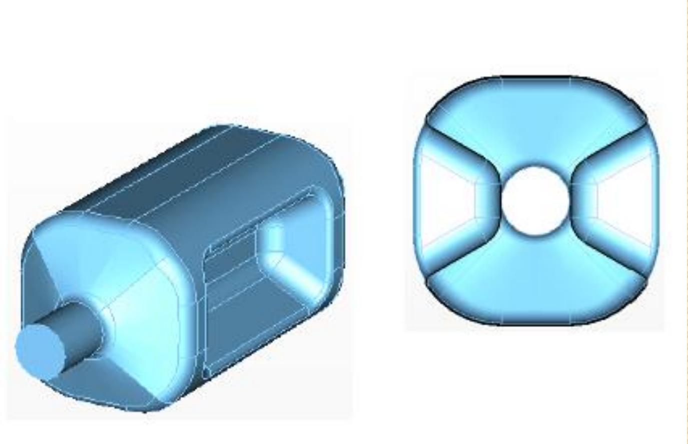


- HOM below (stringent) impedance budget.

J. Delayen: ODU/JLAB Parallel-Bar II

- Flattening field profile OK:
- MP: cavity quite clean; issue maybe in the couplers – under study!
- Engineering design has started: sensitivity to pressure variation done.
- Prototype “square outer conductor”; size 295 mm
- OK @ 3 MV, marginal for 5 MV
- Need full spec!



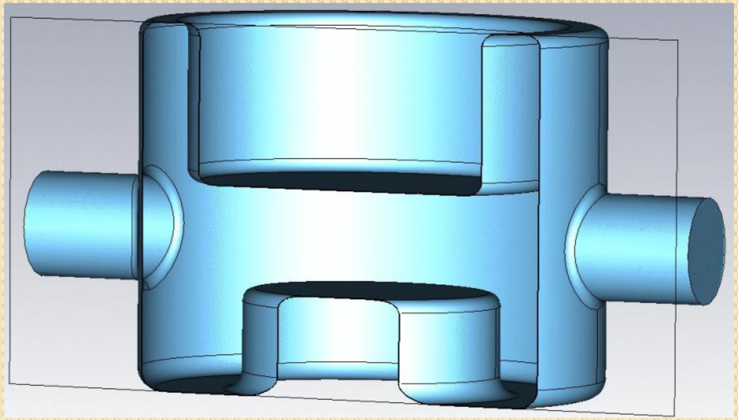


J. Delayen: Parallel bar prototype

- Now building OFC Cu unit:
- End pieces machined from block, side walls stamped from sheet, EBW to join
- testing planned for June 2012.

I. Ben-Zvi, R. Calaga: BNL λ/4 cavity

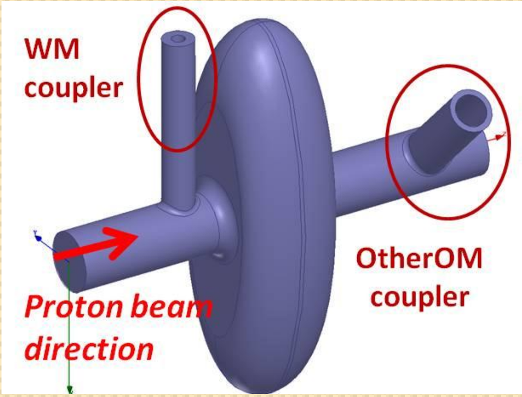
- Spiral2 & ANL reached 70 MV/m and 100 mT
- Compact and simple, mechanically stable.
- Synergy with eRHIC (181 MHz)
- Large separation to next HOM (theor. factor 3, realistically 1.4, high-pass filter enough!)
- Non-zero longitudinal field – issue?
- Easy tuning.
- Field flattening OK (<1% over ± 20 mm)
- MP: easy to condition through.
- Topology similar to double ridge!

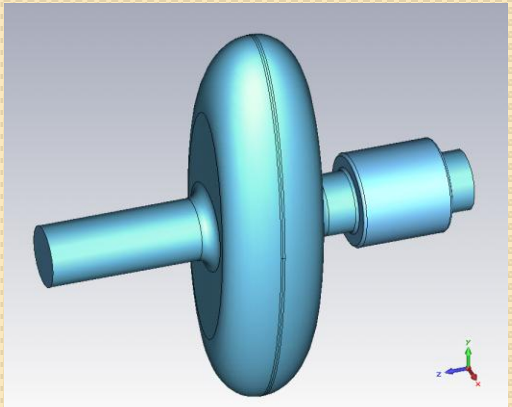


L. Ficcadenti: 800 MHz slim cavity development

- Studied to detail, including power coupling, OOM damping, MP.
- Studied 2 different HOM damping schemes:

1. Working mode rejection system based on a coaxial beam pipe cut-off; working mode leakage too high! With better decoupling, HOM impedance too high.

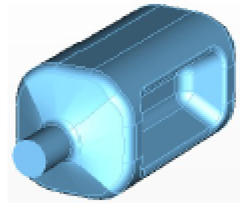


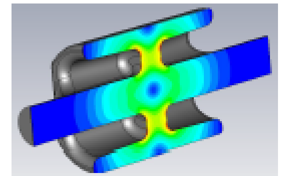


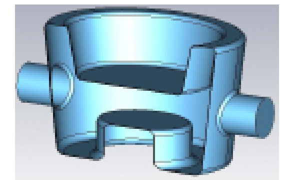
2. Working mode rejected by a TE11 $\lambda/4$ stub resonator (like KEK). MP studies ongoing.

Comparing 400 MHz compacts

400 MHz,
3 MV kick







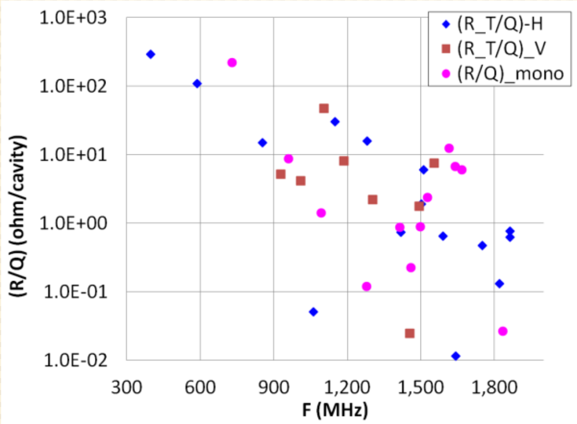
	Modified PB (ODU)	4-Rod (UK)	¼ Wave (BNL)
Cavity Radius [mm]	**147.5**	**143/118**	**142/122**
Cavity length [mm]	597	500	380
Beam Pipe [mm]	84	84	84
Peak E-Field	33	32	47
Peak B-Field	56	60.5	71
R_T/Q	287	915	318
Nearest Mode	584	371-378	575

S. Bousson: Complex shapes

- Probably the most active field in SC RF today.
- Issues addressed by the community:
  - field emission, MP, tuning capabilities, surface treatments
  - Recent progress is remarkable!
- **CC specifications within what has been demonstrated!**

Zenghai Li, ACE3P

- ACE3P: Omega3P, S3P, T3P, Track3P, Pic3P, TEM3P
- Unprecedented accuracy – allows unprecedented problem size!
- Done: ODU/JLAB upgrade cavity HOM content (Omega3P).
- Done: MP barrier prediction (Track3P).



It would be great to use ACE3P codes as common platform to compare the different designs!

Laurent Tavian: testing in **SPS**

- Cryogenic installation, 2K and 4.5 K
- SPS: existing TCF20 (BA4) cryoplant:
  - 4.5 K, 300 kCHF

    Capacity: 0.1 g/s of liquefaction, dynamic RF load 80 W – measured capacity 120 W. OK
  - 2 K pure liquifaction mode, more complicated, requires another heat exchanger and JT valve, 2kW heater, not presently included in CtC, add 150 kCHF + complexity and lower availability.

    Capacity: 0.7 g/s, dynamic RF load 12 W. Marginal – cannot be guaranteed – liquefaction capacity must be measured. Could be done end 2012 – decide then!

P4 cryo upgrade

- Was planned for “global” option – together with cryo upgrade P4, (2018)
- recommended again 4.5 K
  additional cooling 340 W @ 4.5 K
- If 2 K obligatory: add 26 W @ 2 K, add 1 MCHF; space conflict!
- Tendering through 2015 – implementation through LS2 (2018).

P1 and P5

- 2 modules per beam per side of P1 and P5 (8 modules total)
  - 4.5 K: 680 W per IP; 250 W/W – 43 kW total per module
  - 2 K: 104 W per IP; 1000 W/W – 26 kW total per module – globally more efficient.
- Cooling possibilities: via 2 new cryoplants or via the 4 existing sector cryoplants
- If 4.5 K, better to use new IT cryoplants; if 2 K, sector cryoplant looks more logical.

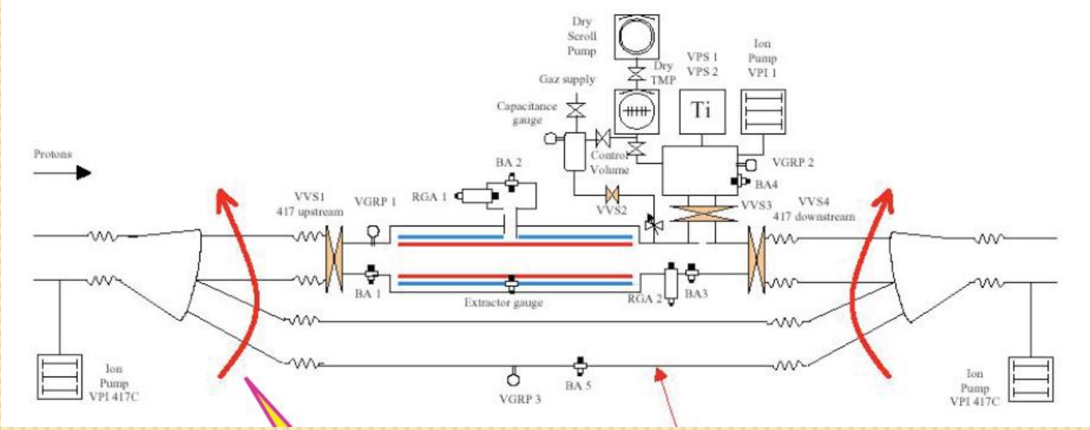
2 K or 4.5 K?

- Decision needed end of 2011! now !! (?)
- Test in LHC P4 as close as possible to final, at 2 K?
- Can it be done at 4.5 K even with cavity designed for 2 K?
- Jörg: added value of test in P4 is significant (emittance BU, MP issues)
- Paul: could the 2 K plant be moved from SPS to LHC P4 for test? Yes, but only for test.

Elias Metral: Tests in SPS

- Reminder of talk as in CC-10 (KEK-B CC)

  KEK-B test was discarded (resources not optimum!)
- Reminder of mass (<500 kg) and size limit (<580 mm)
- Location SPS Point 4 COLDEX.41737 – bypass

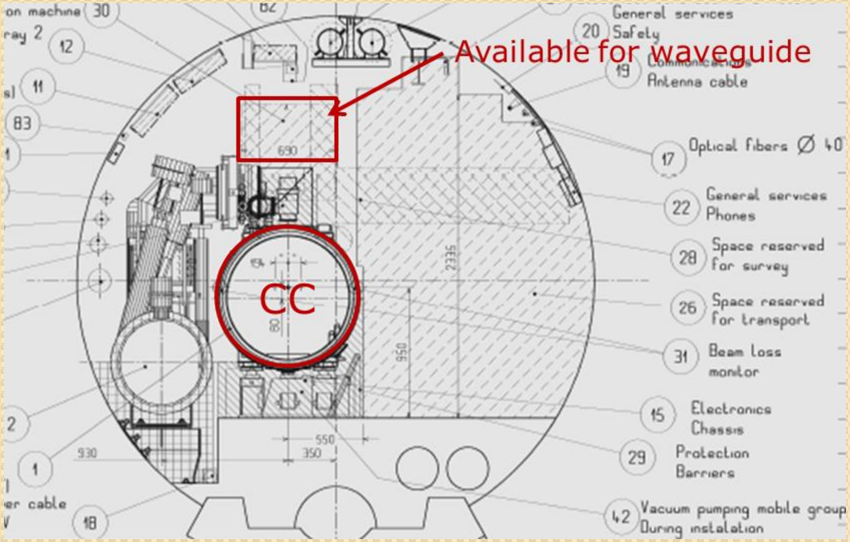


P4 was selected specifically because of KEK-B CC – Compacts could go to other locations

- The installation of RF equipment, amplifiers, etc. must be updated – not yet clear!
- Coordinate with other requests to use COLDEX!
- Can this go elsewhere in the SPS?

Sylvain Weiss: Integration LHC

- P4: almost straight forward; extra cost for 2 K cryo.
- P1 (and similar P5): close to TAN, 150 m from IP (hostile, radioactive!)
- limited space for WG, no space for RF power
- Need the HTS Links to get space!
- Might need some expensive Civil Engineering.



R. Calaga: SPS ε growth MD's

- Goal was: What is the natural emittance growth, what's its source? – is it increased by CC's?
- Tests done at 55, 120 and 270 GeV, Q26:
  - Best: @ 120 GeV with 1.3E10, 18% growth/h both H and V.
- Noise sources culprits: ripple on power supplies, vacuum?
- Transverse damper PU signals could be analysed for coherent signal … what addl' instrumentation is needed?

The additional noise by the CC will be masked in this noise!

HJ Kim: SPS ε growth simulations

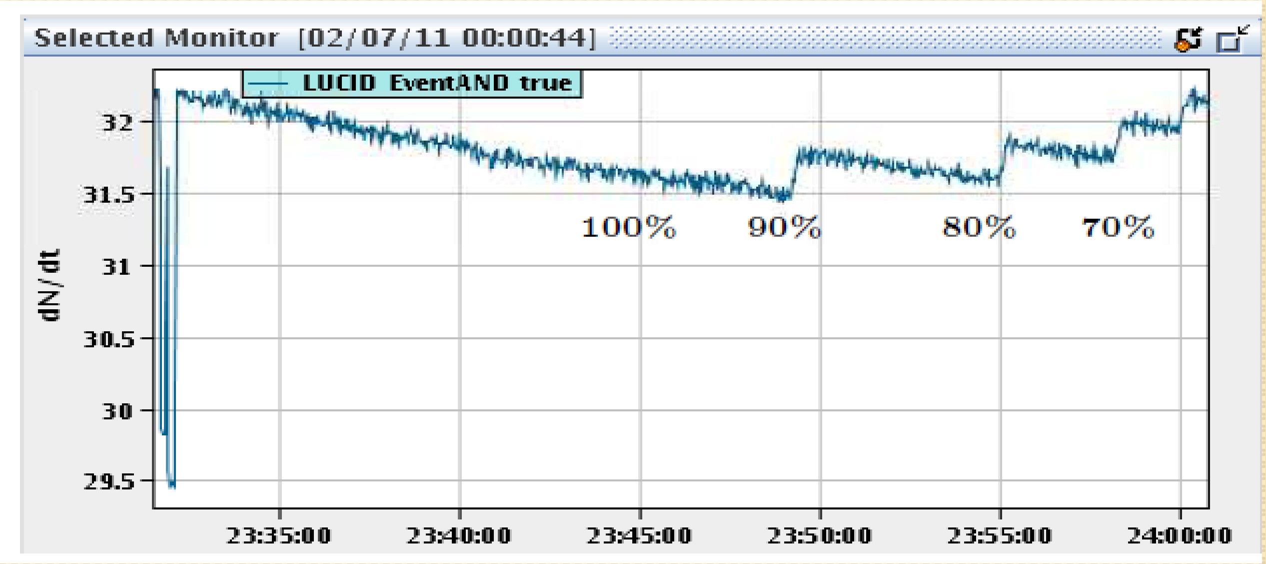
- Simulations done for 55 GeV and 120 GeV
- Dipole noise – simulated for non-realistic noise. What is the ε growth (%/h) for realistic 2.5E-3% noise? (h = 156E6 turns) More study required.
- Space charge – small effect.
- Tune modulation – small effect.
- Multiple Coulomb scattering: simulated 3.9 μrad/h – measured 0.75 μrad/h. Significant! But is it compatible with observations?

W. Herr: Beam-beam in LHC

- LHC runs at lower than nominal ε, larger β^*.
- Achieved ξ well in excess of nominal (0.034) with no ε growth!
- Scan of crossing angle, 12 σ down to 8 σ no effect, dramatic increase of losses below 5 σ. (for 50 ns)
- Small effect on loses, but strong PACMAN effect observed. Predicted offsets confirmed by ATLAS measurement.

W. Herr: Beam-beam in LHC

- Luminosity levelling (at reduced Lumi) by transverse offset routinely done.
- First demonstration of levelling with x-ing angle:



- Beam-beam should allow higher than nominal Lumi – for higher luminosity we need crab cavities.

F. Zimmermann HL-LHC

- Virtual peak luminosity 2E35 needed to level at 5E34
- Trade-off with pile-up; which <μ> is realistic?
- During 2011, scrubbing improved SEY – allowed to go from 75 ns to 50 ns. 25 ns level not quite reached. Heat load at 25 ns?
- Bunch length:
  - nominal 7.55 cm
  - heating concerns below 9 cm
  - 7 cm IBS lower limit (at ε 2 μm)

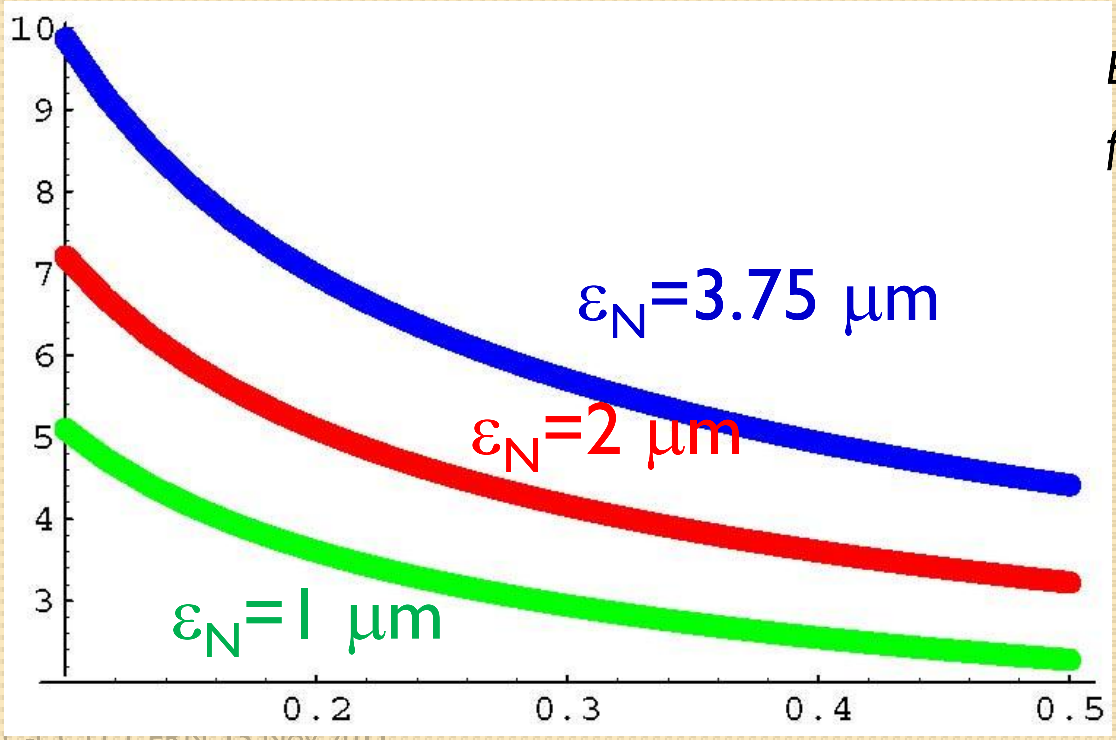
Are these conclusions different if non-gaussian distribution is taken in considerations?

Crab voltage

$$V_{crab} = \frac{cE_0 \tan(\theta_c / 2)}{e 2\pi f_{rf} R_{12}} \approx \frac{cE_0}{e 4\pi f_{rf} R_{12}} \theta_c$$

R_{12}~30-45 m for nominal optics (F.Z., CARE-HHH <Lumi'05)
R_{12} ~24 m for "ATS" upgrade optics (R. De Maria, LHC-CC10)

crab voltage [MV]



E=7 TeV

$f_{RF,crab}$=400 MHz

$V_{crab,RF}$ ~ 5 MV

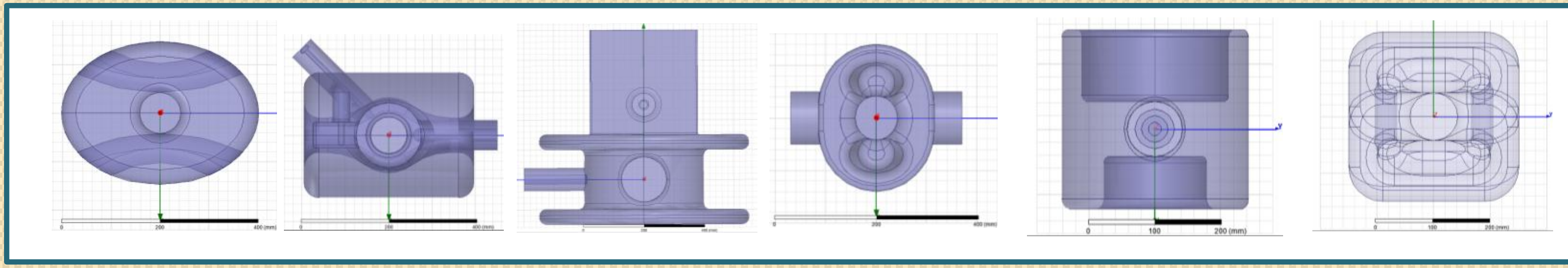
β* [m]

R. DeMaria – Transparent X-ing

- Alternative x-ing scheme (transparent):
  - Present scheme: closed orbit displaced (3.35 mm) at CC location – must be dynamically corrected.
  - New scheme proposed w/o displacement – requires stronger orbit correctors

Field error models

- De Maria, Grudiev



	ODUCAV	SRHW	KEKCAV	UKCAV	QWAVER	FRSCAV
Vz(x=0) [kV]	0.0	-2.1 - 2.5i	-4 +**1378**i	0.0	0 +85.7i	-0.1 -0.2i
Vx [MV]	5	5	5	5	5	5
$B^{(2)}$ [mTm/m]	0	0 -0.04i	-32.7 - 0.1i	0.02 + 0i	25 + 0i	0 +**108**i
$B^{(3)}$ [mTm/m^2]	1250 + 0i	229 + 0i	250 - 0i	**2452** - 0.5i	464 + 0i	-233 +1i
$B^{(4)}$ [mTm/m^3]	0	0	266 - 5i	0	540 +0i	-189 -**14209**i

- R. Appleby presented a more general approach using vector potential and Taylor maps.

J. Barranco: CC Multipoles

- Linear Tuneshifts (b2): for the worst case: 1.4E-2, comparable beam-beam 0.02 – this is the dominant effect. Realistic cavity: < 1E-3.
- Nonlinear terms are negligible:
  - Tune shift with amplitude (b4)
  - Chromaticity shift (b3)
  - Coupling with D (b3)
- MAPCLASS upgraded to include CC's
- Effect due to CC negligible.
- Time-dependent multipoles should be implemented in Sixtrack for long-term stability

R. Assmann: Load on collimators

- Hierarchy must be respected by CC's.
- Local scheme preferred – failure modes to be studied.

T. Baer: Machine Protection

- For upgraded optics, one gets 4 σ offset at CC voltage maximum. (10 MV kick, single cavity)
- Dynamics dominated by Q_{ext}. (τ = 1 ms for 1E6)
  - up to 0.5 σ per turn! 2.2 σ after 5 turns.
  - Voltage failure – bunch centre not affected
  - Phase failure – bunch centre affected
- Scenarios to stay below 1 MJ loss in 5 turns:

	Scenario 1: $\beta^* = 30cm$	Scenario 2: 800 MHz or Independent CCs	Scenario 3: large Q_{ext}
CC frequency (f)	400 MHz	400 MHz / **800 MHz**	400 MHz
Number of independant CCs (n_{cc})	1	**2** / 1	1
Q_{ext}	1‘250‘000	1‘250‘000	**2‘000‘000**
β^*	**30 cm**	15 cm	15 cm
Fraction to be depleted below 1MJ.	1.1σ	1.1σ	1.5σ

- Hollow electron lens to deplete tails gives add’l failure margin.

Beam stability & Impedance issues

- Light water-bagging of PDF allows to insure Landau damping w/o increasing longitudinal ε.
- A. Burov gave new numbers for impedance budget (less stringent☺):
  - For ultimate LHC-CC parameters, the longitudinal HOM impedance may not exceed 0.6 MOhm per cavity at the revolution harmonics.
  - The transverse HOM may not exceed 1.5 Mohm/m per cavity.
- For stability, *Q* should be below 1E4 – how to reach this?

K.Ohmi: RF noise & X-ing angle

- Experimental studies with noise injection performed at KEK analysed and explained
- Above beam-beam tune shift of 0.02 sensitive to noise.
- Above 0.03 sensitive to Piwinski angle

S. Paret: Beam-beam simulations

- Strong-strong, including crabs, FB and noise
- numerical noise equivalent to 0.5%/h ε growth
- 1%/h requires noise < 4 nm
- this latter requires phase stability 0.22 mrad
- White BPM noise of 2 μm results in 7.7%/h ε growth

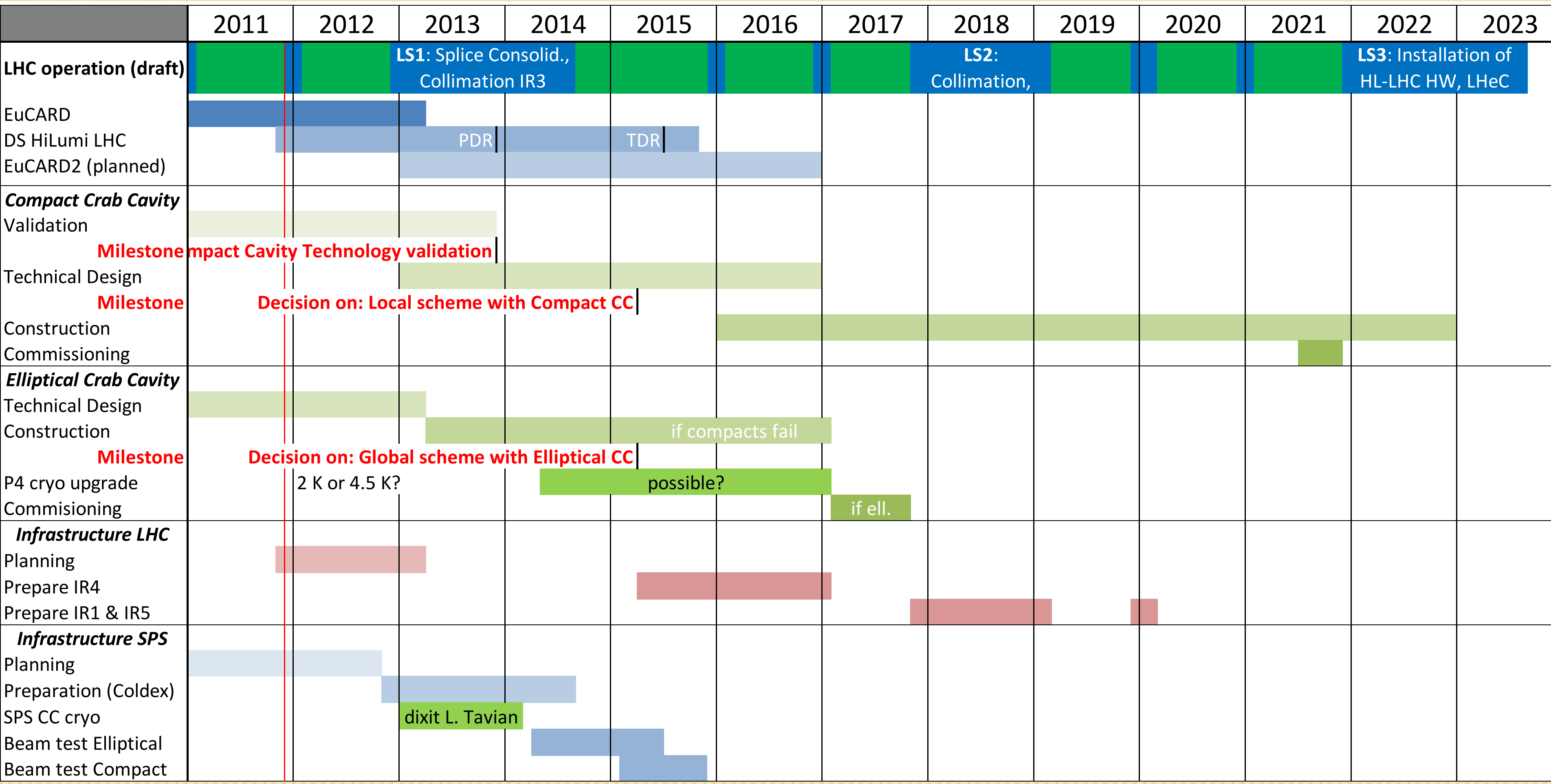
S. White: Synchro-betatron Studies

- Crabs can damp the synchro-betatron sidebands excited by a crossing angle.
- The Piwinski-angle regime of HL-LHC (2 to 3) is unknown territory.
- LR effects are much worse for HL-LHC parameters – to recover a more clean footprint one has to increase the crossing angle to 12 σ separation. More detailed studies needed.
- CC are required to reach design goals (help to recover clean footprint).

P. Baudrenghien, LLRF etc.

- LLRF inspired by LHC acceleration system – integration with it straight forward:
  - Direct RF FB (limited by τ_{group}) and *R*/*Q*,
  - plus betatron comb (like 1-turn) reduces *Z* by another factor 6 or so.
- Phase noise 5E-3° rms @400 MHz to be expected, reduced by FB and further more by betatron comb filter.
- Linear Quadratic Regulator allows smarter control – to be studied in detail.
- Proposed scenario: keep small field for tuning system to work. 2 cavities could be counter-phased for zero voltage.

HL-LHC Crab Cavities planning



Next steps

- **1.9 K or 4.5 K?**
  - My personal opinion (EJ): design for 1.9 K (larger field, no bubbles). Answer the question what relevant information you can get from a test @ 4.5 K!
- **Refine SPS test needs and goals:**
  - SPS tests highly desirable (LHC is NOT a test bed!)
  - COLDEX resulted from KEK-B CC test – are there other possible locations for compact CCs? Do we need the bypass? Do we understand SPS well enough to arrive at conclusions? Studies needed!

More Questions

- **Refine cryoplant upgrade plan!**
  - Former LHC P4 cryo needs were for a full-fletched solution (global scheme) – what about a "small" temporary solution just for a test? (maybe the one used before in SPS)
- **Test in LHC P4**
  - LHC time is very precious – one should do everything possible to do relevant tests in SPS (and as early as possible)
  - Final qualification will however need LHC test for those aspects that cannot be addressed in SPS. To be scheduled!

More Questions

- **What happens to the unbunched beam?**
- How to progress with the cryomodule? Soon needed for SPS test – later for final cryostat. Synergy with FNAL and others should be explored!