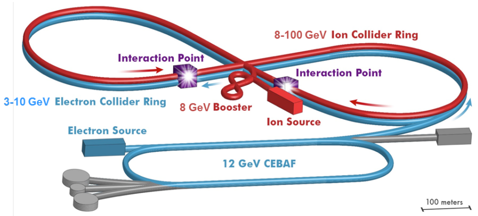
Crab Cavity Efforts at CERN

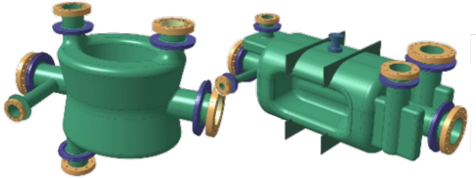
Alejandro Castilla on behalf of the BE-RF-SRF section and HL-LHC Project Work Package 4, with special thanks to (but not only) Lancaster University, USLARP, ODU, Jefferson Lab, and more…

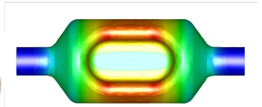
Jefferson Lab - Accelerators Seminar, December 15th 2016

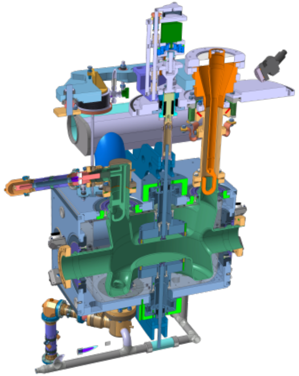
Outline

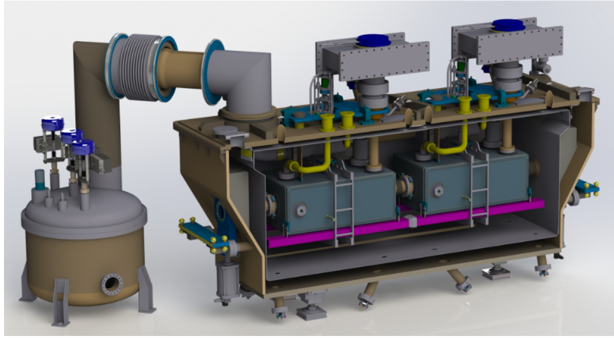
- Luminosity Requirements
  - Jefferson Lab Electron-Ion Collider
  - HL-LHC
- Crab Cavity Designs
- Schedule
- Activities at CERN
- Summary



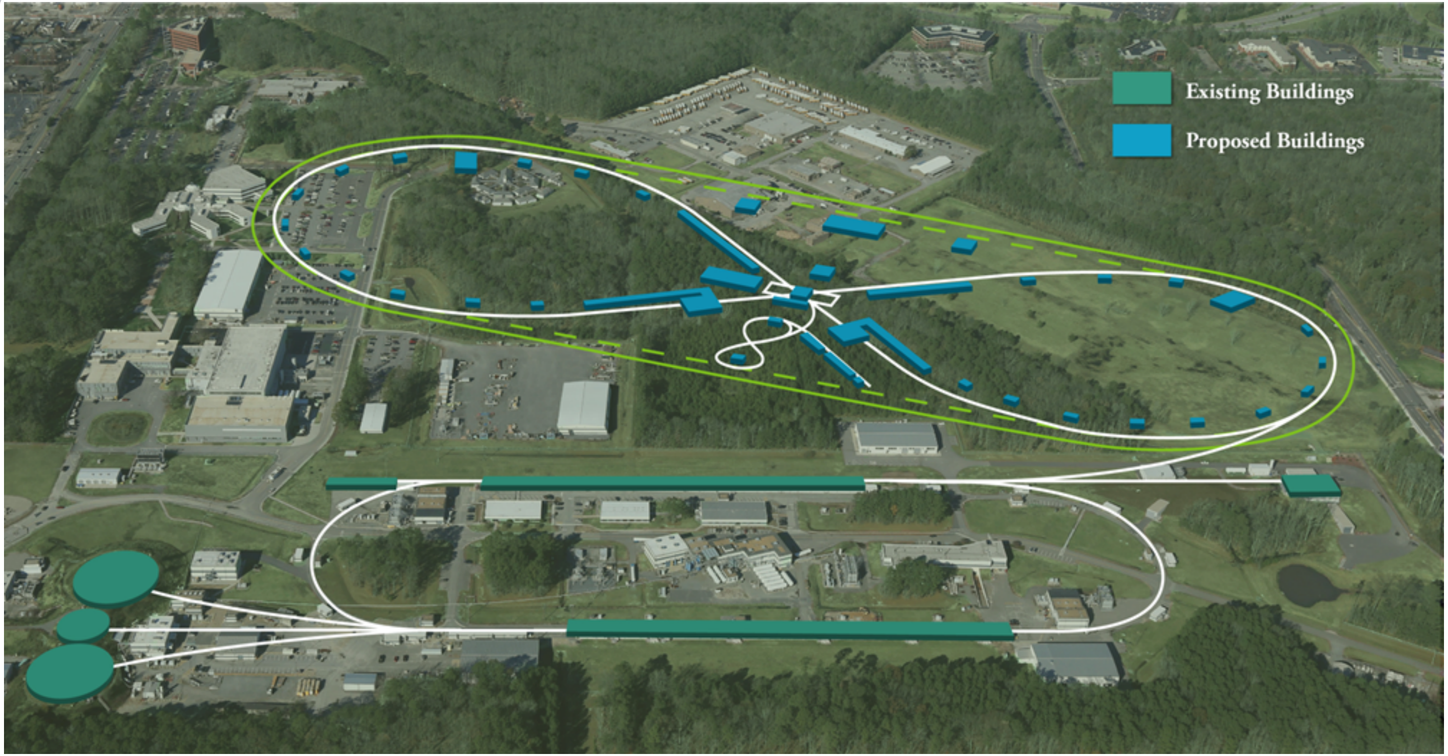






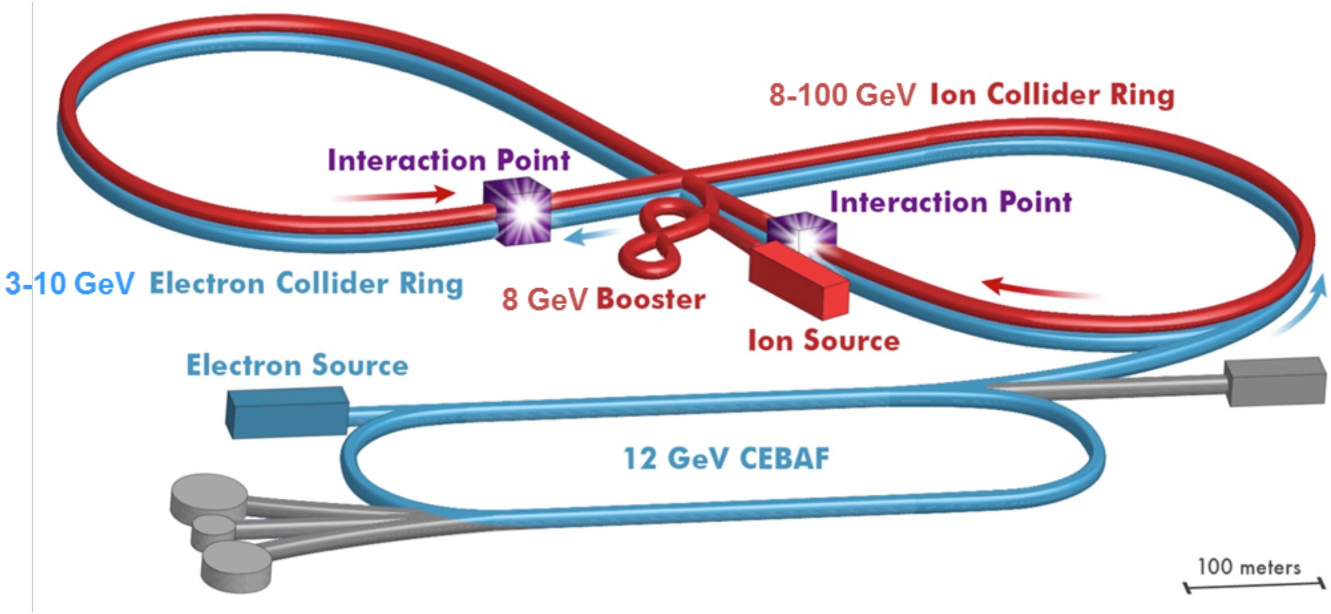


Jefferson Lab - EIC



*from F. Pilat, JLEIC Collaboration Meeting 5th – 7th Oct 2016

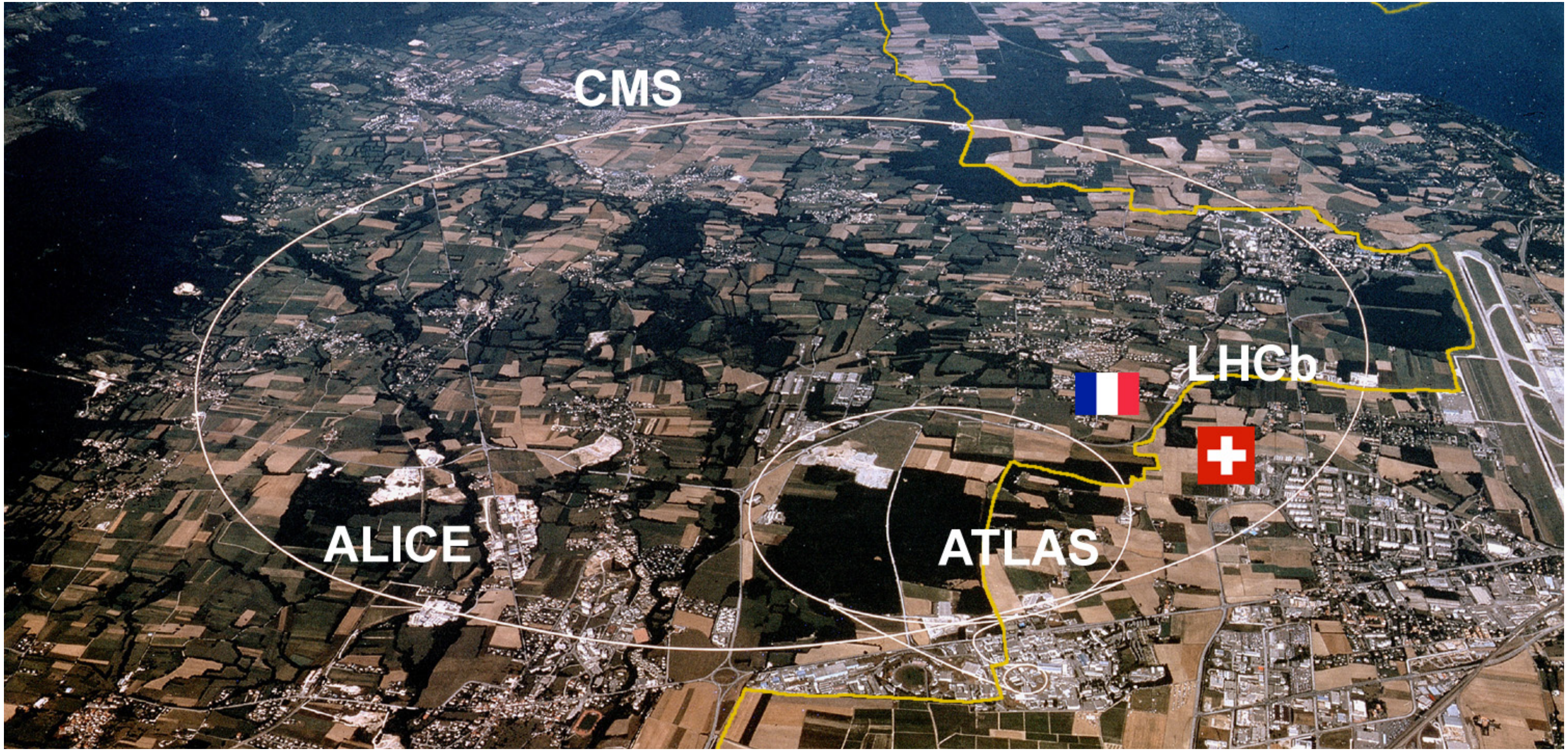
Jefferson Lab - EIC



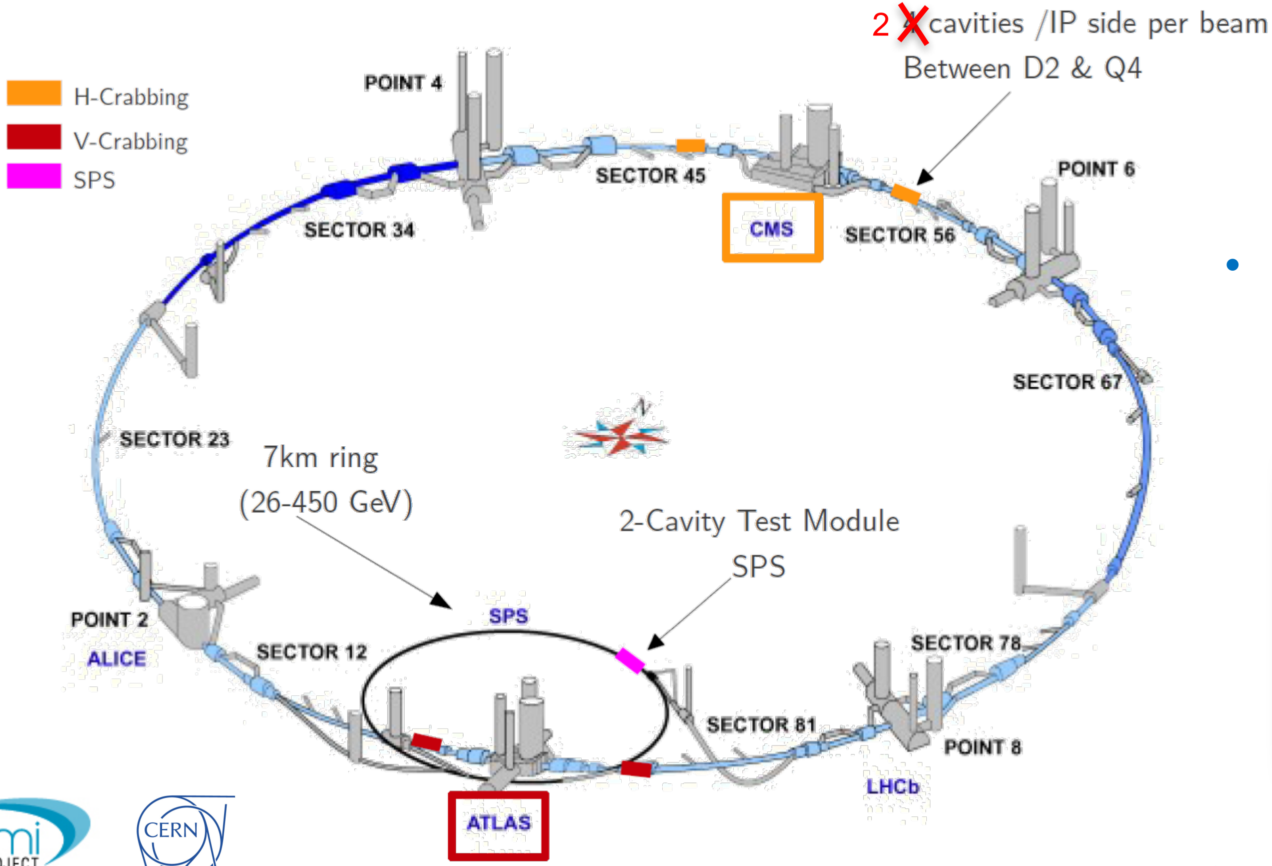
- $(\sqrt{s} = 20 - 70\ GeV)$ and $> \mathbf{10^{33}}\ \boldsymbol{cm^{-2}s^{-1}}$ **luminosity**

*from V. Morozov, JLEIC Collaboration Meeting 5th – 7th Oct 2016

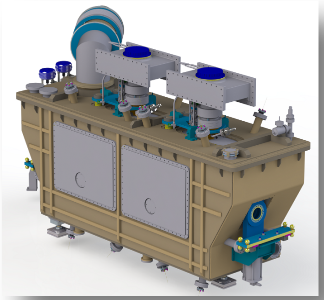
CERN HL-LHC Upgrades



CERN HL-LHC Upgrades



- $\sim 10^{34}\ cm^{-2}s^{-1}$ **peak luminosity**

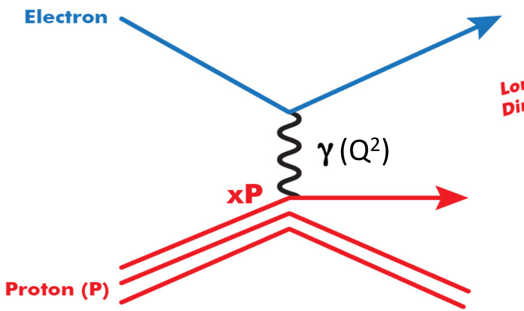


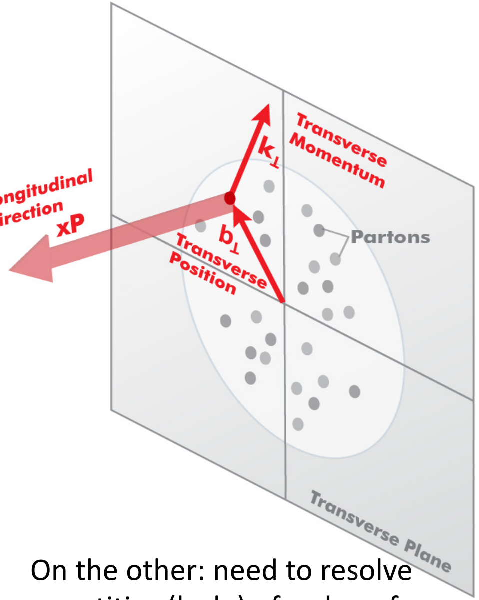
Comparing the Machines

		JLEIC		HL-LHC
Parameter	**Units**	**p**	**e**	**p**
Beam energy	GeV	100	5	7000
Collision frequency (***SRF1***)	MHz	476		400
Particles per bunch	10^{10}	0.98	3.7	22
Beam current	A	0.75	2.82	1.1
Polarization (***BDD1***)		>70%	>70%	--
Bunch length, rms	cm	1.2	1.2	9.0
Norm. emittance, x/y (***ECL***)	μm	**0.5/0.1**	**70/14**	**2.5**
x/y β^* (***BDD2***)	cm	**6/1.2**	**4/0.8**	**20**
Vert. beam-beam param. (***BDD3***)		0.015	0.053	0.0086
Lumi./IP, w/HG, 10^{33}	**$cm^{-2}s^{-1}$**	**19.5**		**59.5**

Experimental Challenge of the EIC

$s = xyQ^2$, $s = 4E_eE_p$



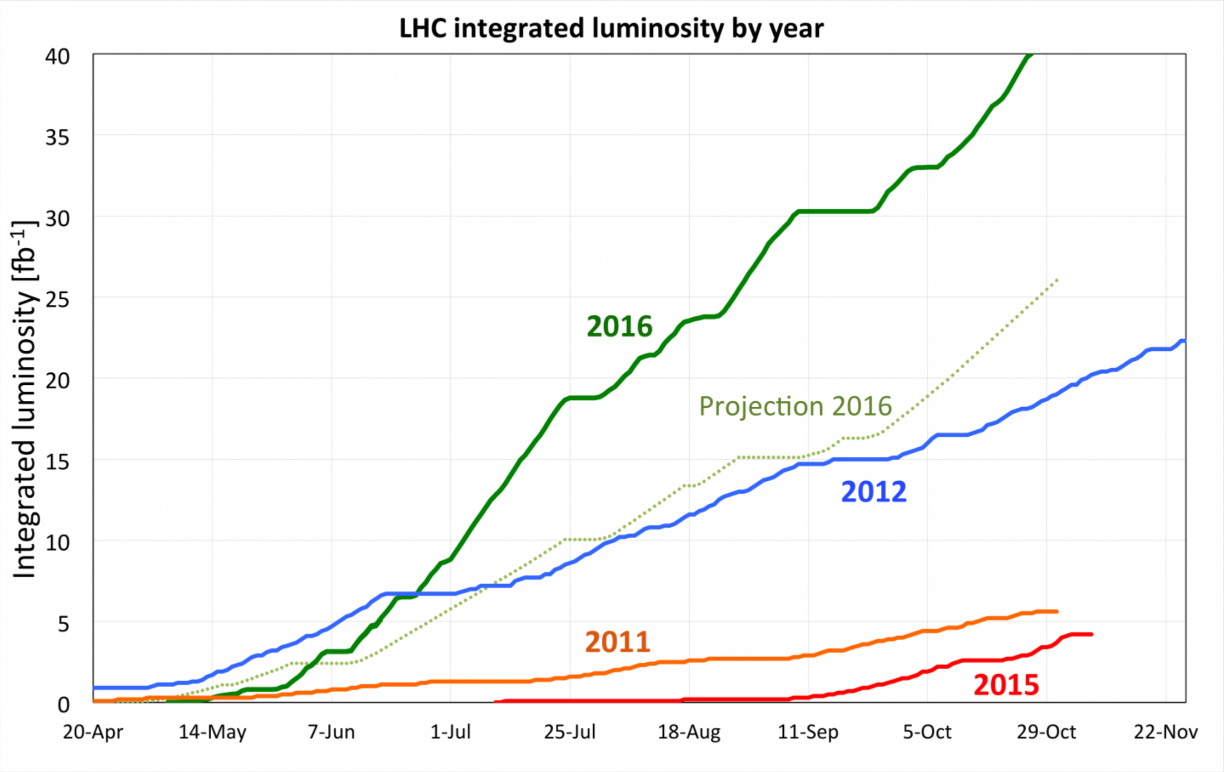


On one hand: need high beam energies to resolve partons in nucleons.
Q^2 needs to be up to ~1000 GeV^2

On the other: need to resolve quantities (k_t, b_t) of order a few hundred MeV in the proton. Limits proton beam energy. High Lumi needed.

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

LHC 2016 Run (about luminosity)



https://home.cern/cern-people/updates/2016/10/lhc-report-end-2016-proton-proton-operation

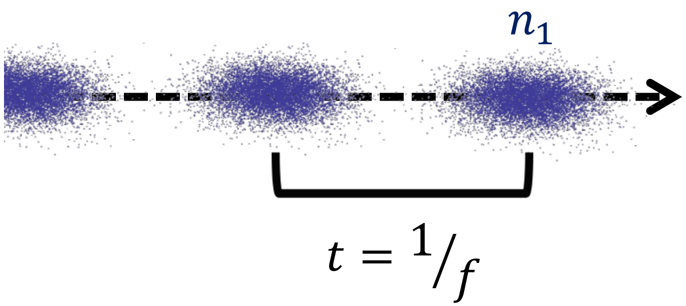
Luminosity in Colliders

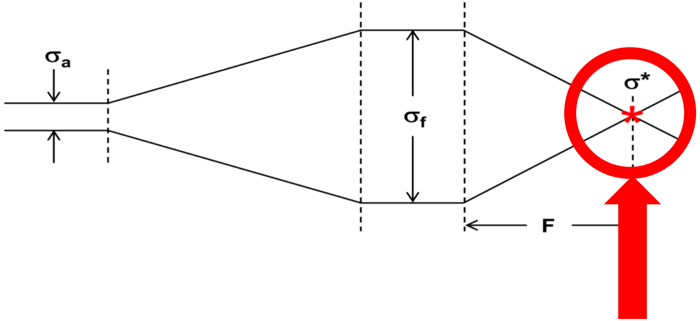
- More events in time → better statistic/resolution of the processes

$$\frac{dR}{dt} = \mathcal{L} \times \sigma_p$$

  - $\frac{dR}{dt}$ interactions per second,
  - σ_p interaction cross section (machine independent),
  - $\mathcal{L}$ luminosity, relativistic invariant, independent of the interaction and –very important- measurable.

Luminosity in Colliders





- Identical Gaussian beams
  - no crossing angle
  - w/o dispersion
  - no offset

$$\mathcal{L} = \frac{n_1 n_2 f N_b}{4\pi\sigma_x\sigma_y}$$

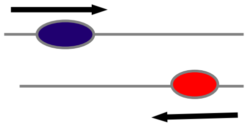
- Where at the IP

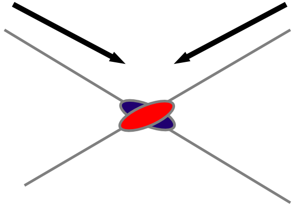
$$\beta^*_{x,y} = \frac{\sigma^2_{x,y}}{\epsilon} \quad \text{and} \quad \epsilon = \frac{\gamma}{\epsilon_N}$$

$$\therefore \mathcal{L} = \frac{n_1 n_2 f N_b}{4\pi\epsilon\sqrt{\beta^*_x\beta^*_y}}$$

Luminosity Parameters

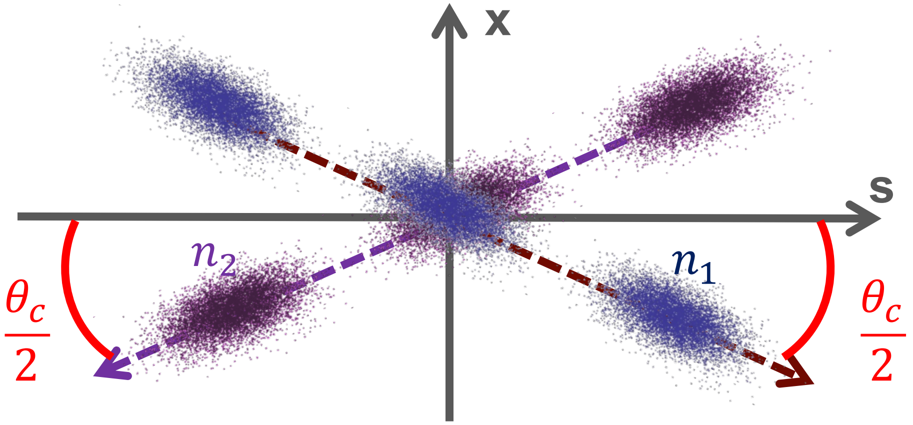
- Geometrical deformations at IP (hour-glass)
- Beam offsets
- Dispersion at IP
- Strong coupling, etc.
- Not head-on (crossing angle θ_c)





$$\mathcal{L} = \frac{1}{4\pi}\underbrace{(nfN_b)}_{\text{total beam current}} \cdot \overbrace{\frac{n}{\epsilon_N}}^{\text{injector \& beam-beam}} \cdot \underbrace{\frac{\gamma}{\beta^*}}_{\text{energy \& squeeze}} \cdot \overbrace{R(\theta_c, \epsilon, \beta^*, \sigma_s)}^{\text{Reduction factor: hourglass effect, crossing angle…}}$$

Crossing Angle



- Using rotated reference frames per beam
  - change of coordinates
  - rewrite Gaussian distributions
  - compute the new Gaussian integrals

Luminosity + Crossing Angle

- Some more approximations since ${}^{\theta_c}/_2$ is small:

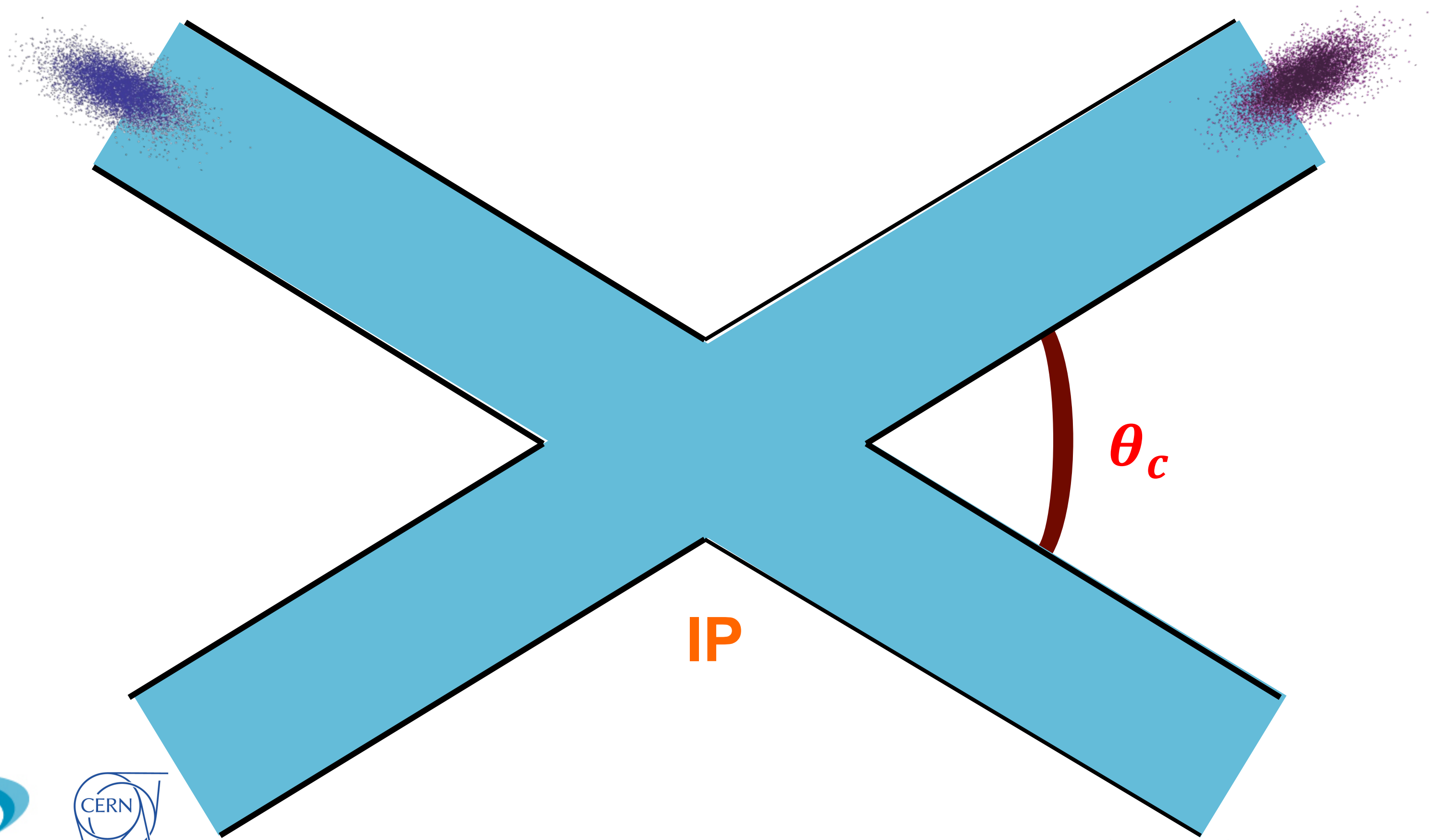
$$\sin {}^{\theta_c}/_2 \sim \tan {}^{\theta_c}/_2 \sim {}^{\theta_c}/_2 \, ;$$

discarding $\begin{cases} {\sigma_x}^k \sin^l {}^{\theta_c}/_2 \\ x^k \sin^l {}^{\theta_c}/_2 \end{cases} ; \ \forall \, k + l \geq 4$

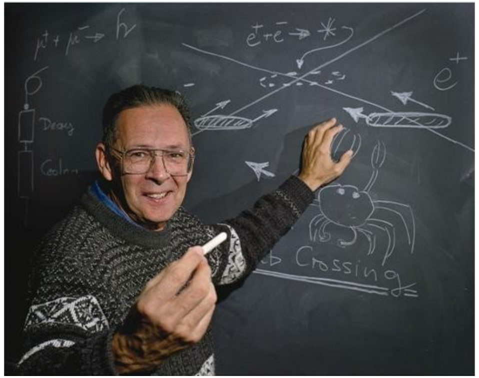
- And so the result is slightly different:

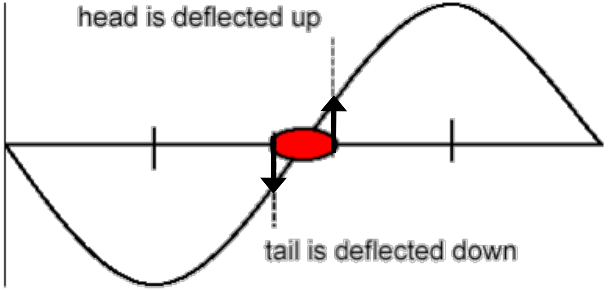
$$\mathcal{L} = \frac{n_1 n_2 f N_b}{4\pi\epsilon\sqrt{\beta_x^* \beta_y^*}} \cdot \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\frac{\theta_c}{2}\right)^2}}$$

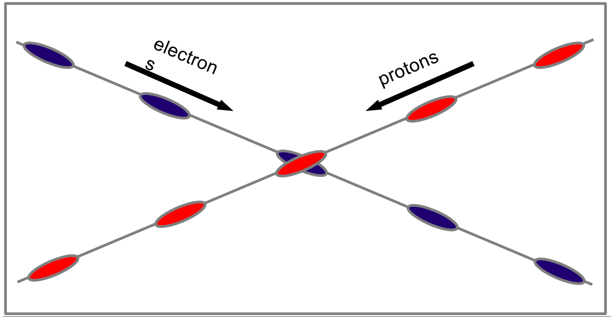
Crossing Angle w/o Correction

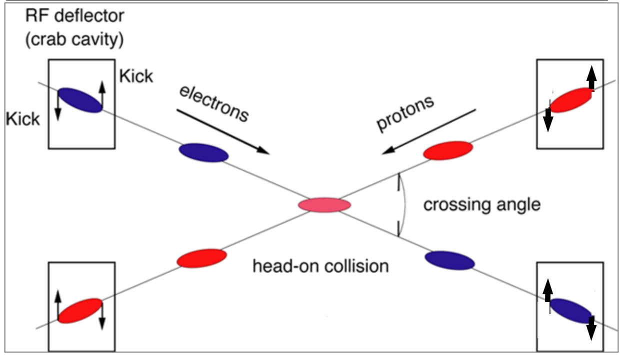


The Crabbing Concept





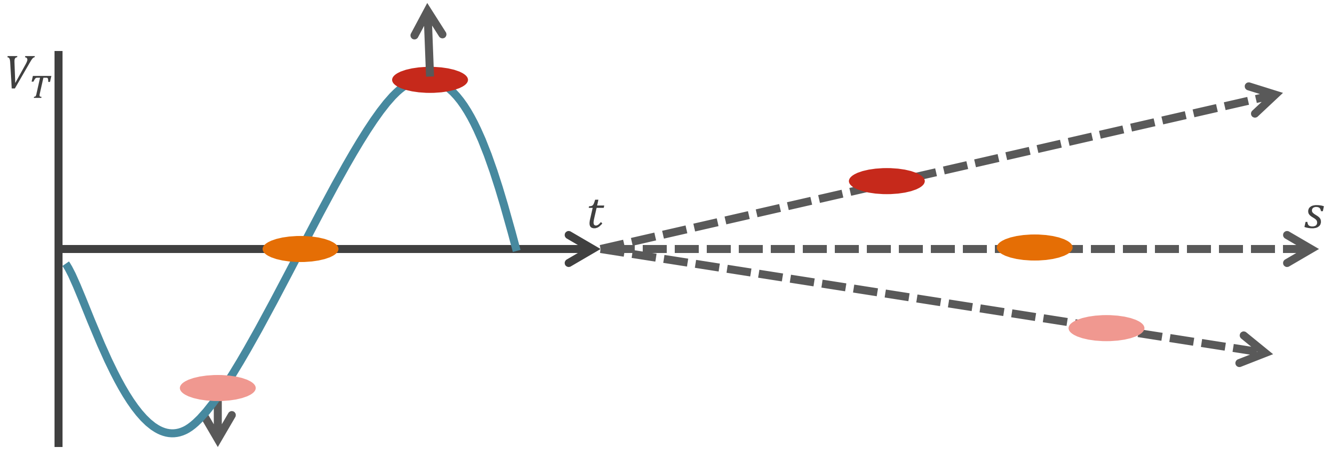




*R. Palmer, SLAC-PUB-4707 (1988).

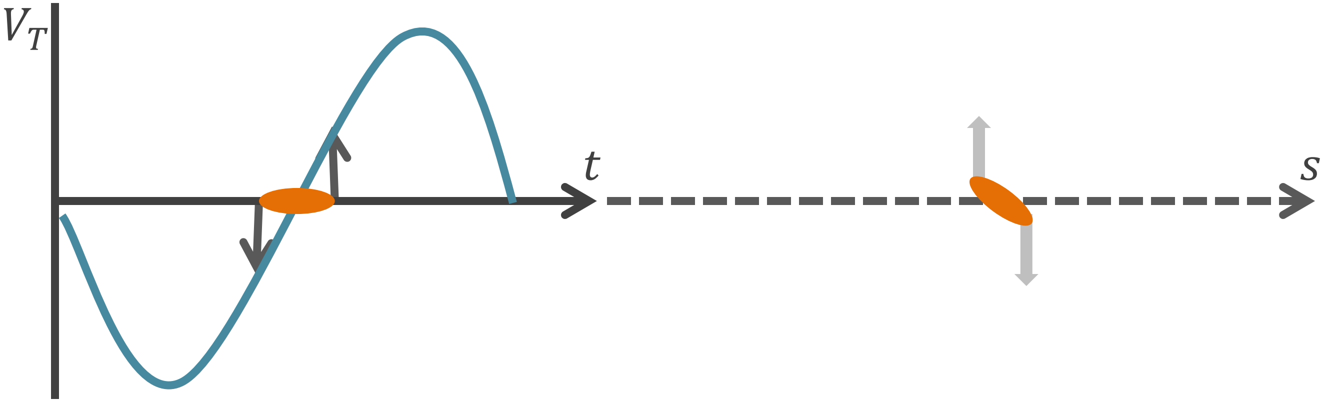
RF Transverse Deflection

$$V_T = \int_{-\infty}^{\infty} \left[E_x(z) \cos \frac{\omega z}{c} + cB_y(z) \sin \frac{\omega z}{c} \right] dz$$

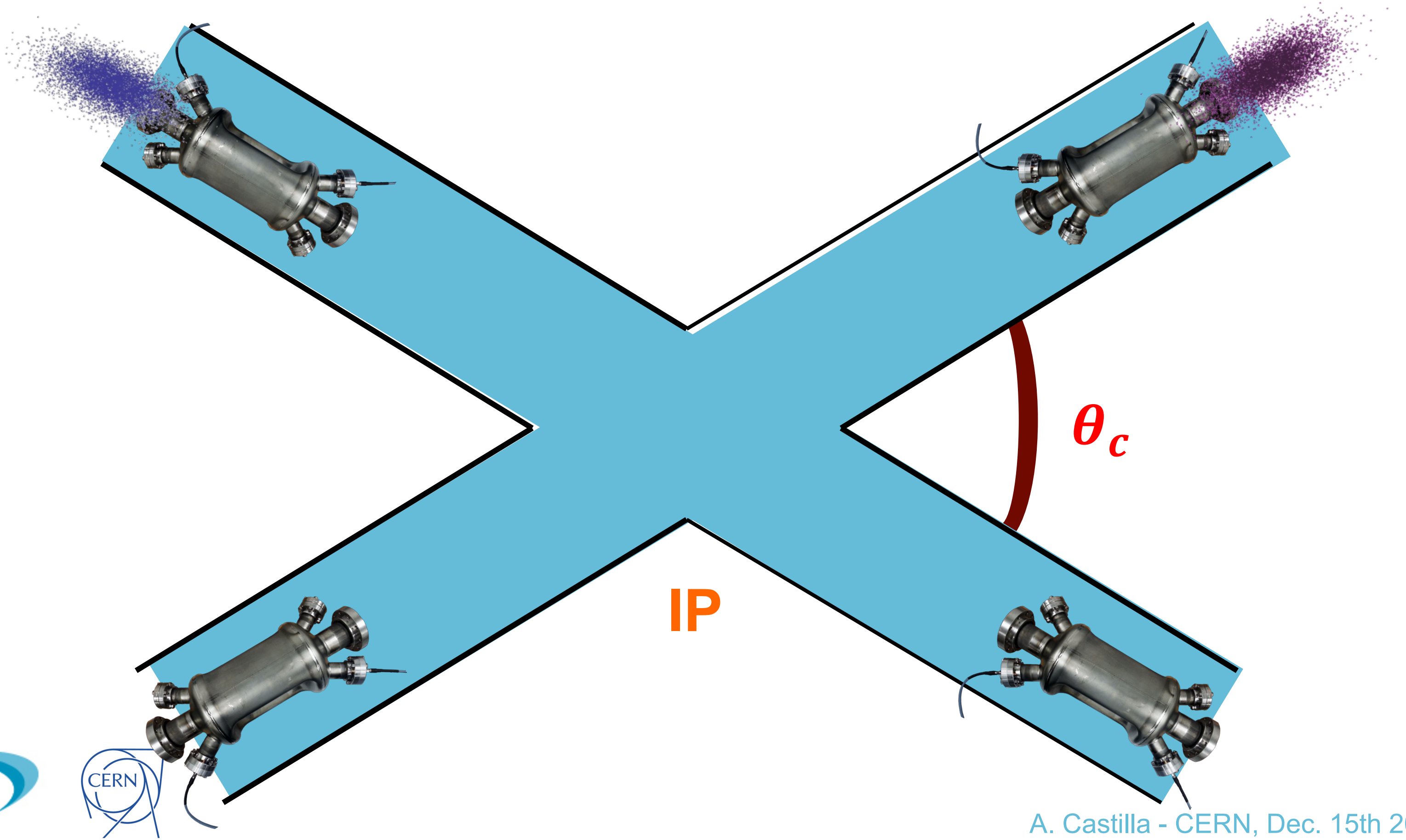


RF Crabbing

$$V_T = \int_{-\infty}^{\infty} \left[E_x(z) \cos \frac{\omega z}{c} + c B_y(z) \sin \frac{\omega z}{c} \right] dz$$



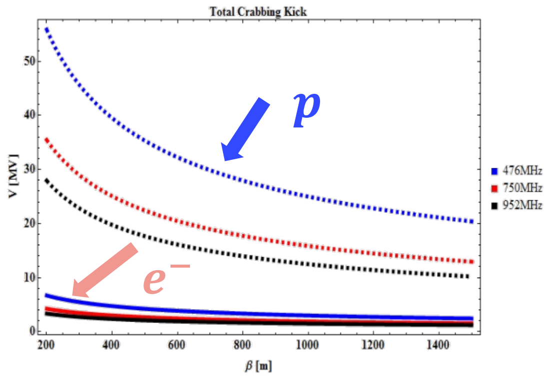
Local Crab Crossing Correction



Comparing Machine Requirements

$$V_T = \frac{c E_b \tan\frac{\theta_c}{2}}{\omega\sqrt{\beta^* \beta^c}}$$

JLEIC*



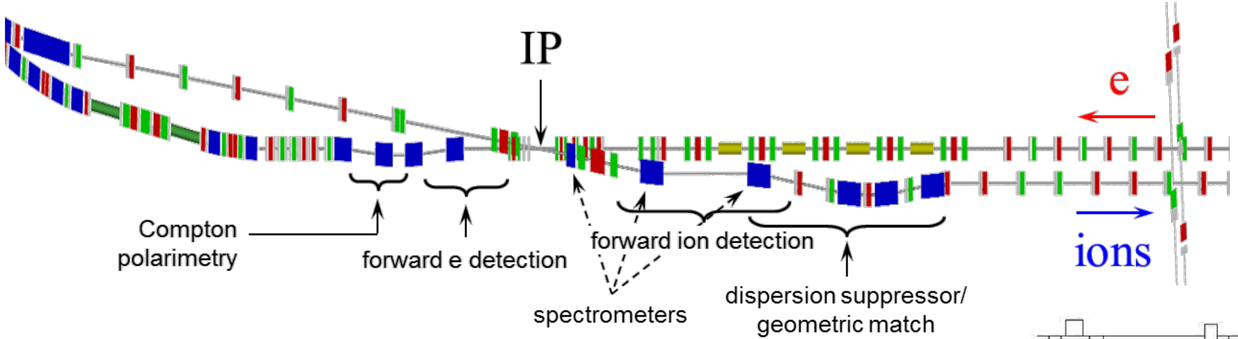
*from S. De Silva, JLEIC Collaboration Meeting 5th – 7th Oct 2016

HL-LHC

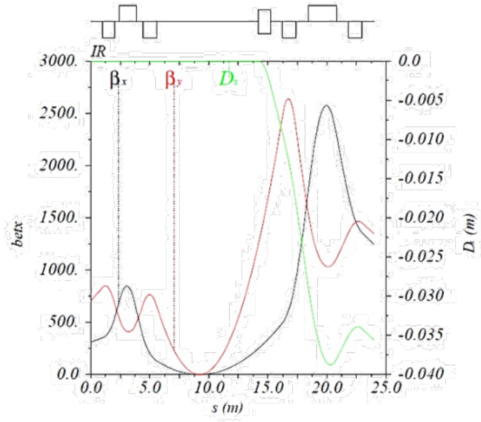
Parameter	Proton	Units
Beam energy E_b	7000	GeV
Beam current	1.1	A
Bunch frequency ω	400	MHz
Crab crossing angle θ_c	~0.5	mrad
Beta function at IP β^*	20	cm
Beta function at CC β^c	~3000	m
Integrated kicking voltage per beam per side V_T	**~8.5**	**MV**

Parameter	Electron	Proton	Units
Beam energy E_b	10	100	GeV
Beam current	0.72	5.0	A
Bunch frequency ω	952.6		MHz
Crab crossing angle θ_c	**50.0**		mrad
Beta function at IP β_x^*	10		cm
Beta function at CC β_x^c	200	750	m
Integrated kicking voltage per beam per side V_T	**2.8**	**14.5**	**MV**

JLEIC Interaction Region



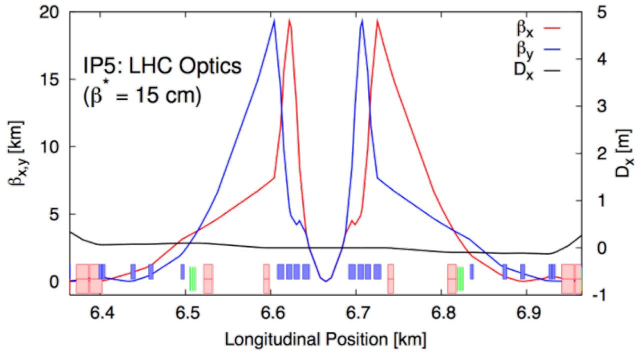
- 50 mrad crossing angle
  - Fast beam separation
  - No parasitic collisions
  - Improved momentum resolution for the detector
- Other advantages
  - Downstream chicane for electrons
    - spectrometry and polarimetry
  - e's & p's parallel and separated downstream by 1.5 m

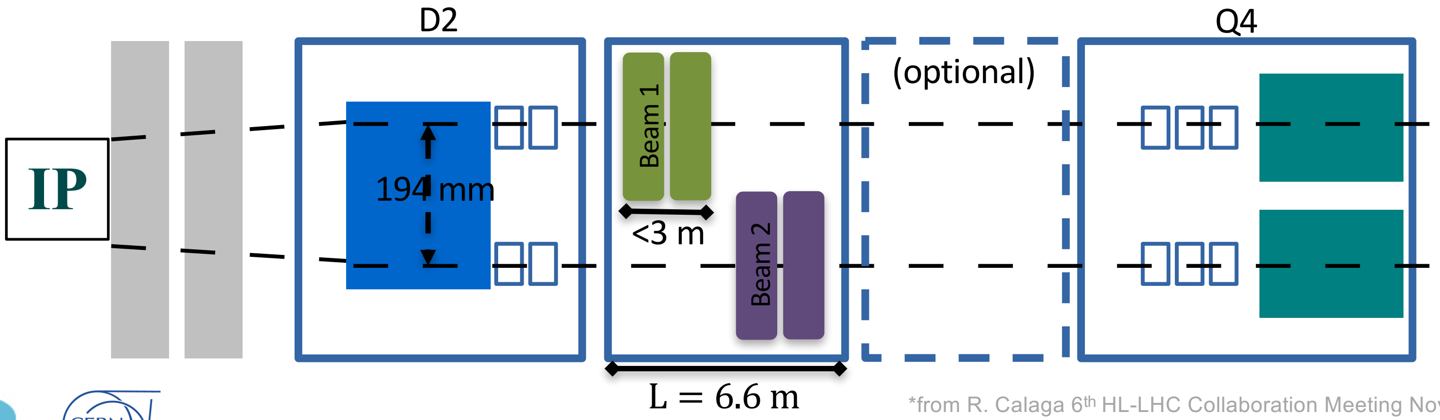


*from V. Morozov, JLEIC Collaboration Meeting 5th – 7th Oct 2016

Reminder, Basic Parameters

- Voltage = **3.4 MV /cavity** (2 cavities /beam /IP side) – 16 total
- Frequency = 400.79 MHz
- $Q_{ext} = 5\times10^5$, $Q_0 \approx 10^{10}$
- RF power source = 80 kW (SPS ≤ 40 kW)
- Cavity tuning = ±100 kHz (LFD ~ 0.5 kHz)
- Operating temperature = 2.0 K



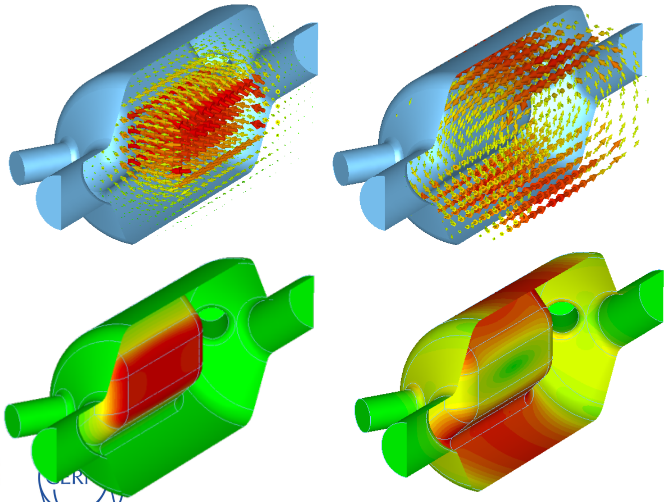


*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016

750 MHz-RFD Transverse Kick

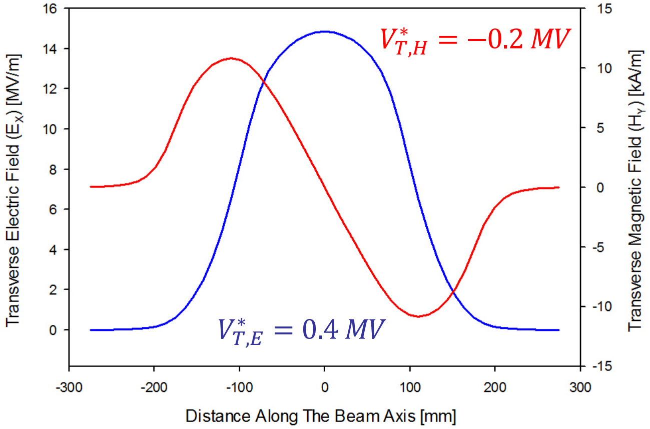
$$V_T = \int_{-\infty}^{\infty} \left[E_x(z) \cos\frac{\omega z}{c} + cB_y(z) \sin\frac{\omega z}{c} \right] dz$$

Electric Field **Magnetic Field**



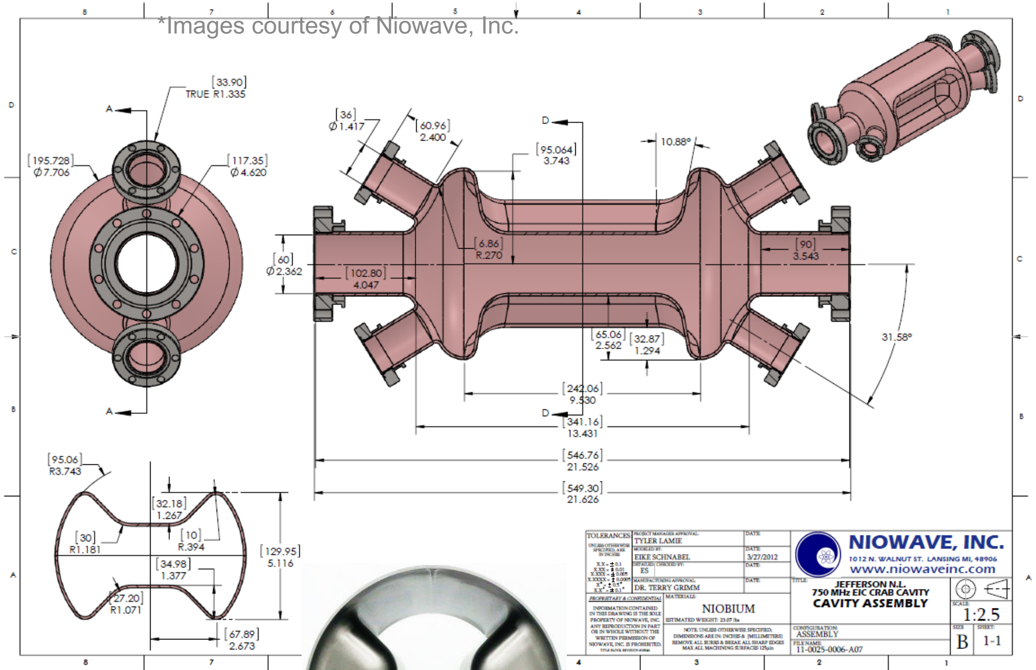
$$E_T = \frac{V_T}{\lambda/_2} \Rightarrow V_T^* = 0.2\ MV$$

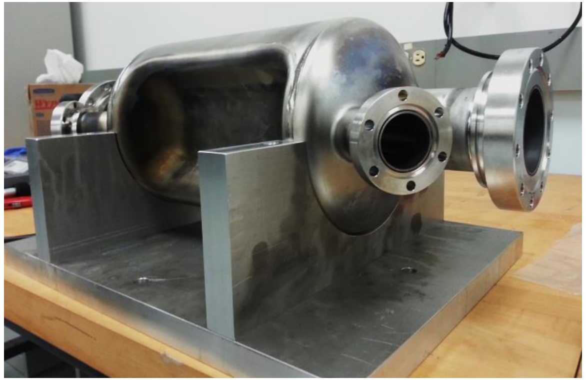
$$E_T^* = 1\ {}^{MV}/_{m}$$



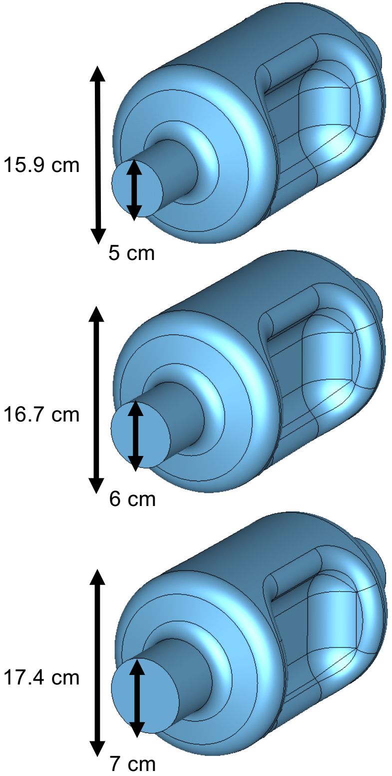
750 MHz MEIC-Crab Fabrication

*Images courtesy of Niowave, Inc.





952.6 MHz Cavity – Single Cell Cavity



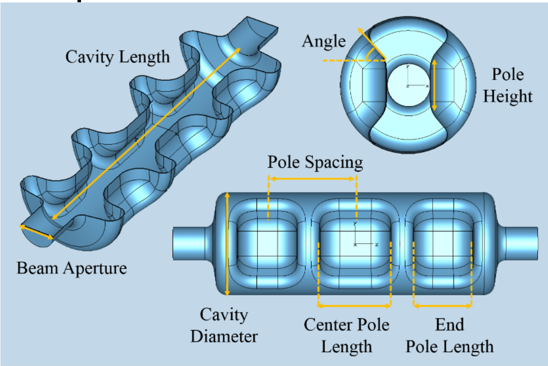
- Single cell cavity designs with varying beam aperture radii
- RF properties
  - Peak surface fields increase
  - Shunt impedance decrease

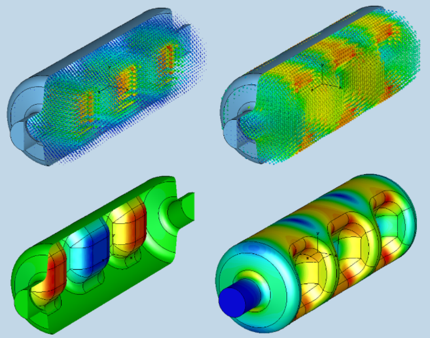
	(A)	(B)	(C)	
Frequency		**952.6**		**MHz**
Aperture	50	60	70	mm
1st HOM	1431.0	1420.4	1411.5	MHz
V_t^*		0.157		MV
E_p^*	4.2	4.8	5.4	MV/m
B_p^*	9.3	11.3	13.6	mT
$[R/Q]_t$	136	81	50	Ω
G	145	155	166	Ω
R_tR_s	2.0×10^4	1.3×10^4	8.3×10^3	Ω^2
$^*E_t = 1$ MV/m				

*from S. De Silva, JLEIC Collaboration Meeting 5th – 7th Oct 2016

952.6 MHz Cavity – Multi-Cell Cavity

- A 3-cell design study with varying beam aperture





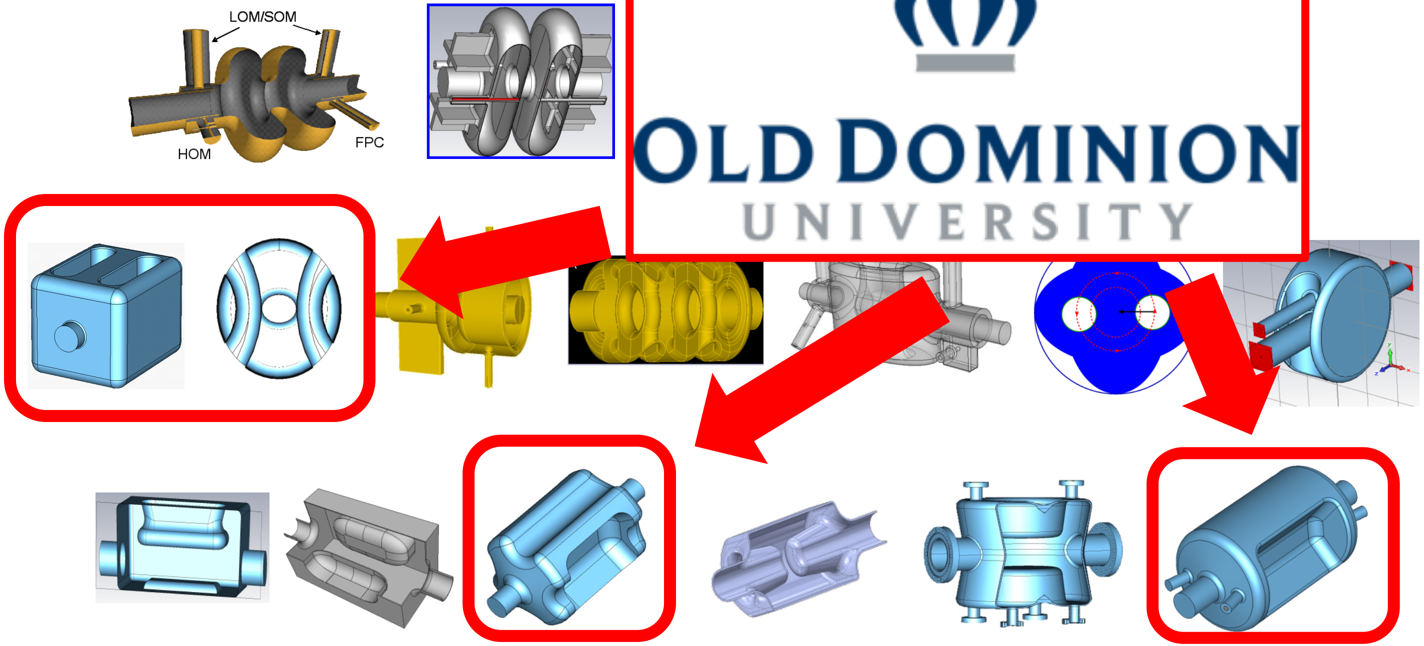
- Low surface fields
- High shunt impedance
- Presence of lower order modes
  - Requires a notch filter in damping LOMs

	(A)	(B)	(C)	
Frequency		**952.6**		**MHz**
Aperture	50	60	70	mm
LOM	790, 879	773, 870	757, 862	
1st HOM	1409	1383	1335	MHz
V_t^*		0.157		MV
E_p^*	4.7	5.1	5.6	MV/m
B_p^*	8.7	10.0	11.4	mT
$[R/Q]_t$	494	323	219	Ω
G	161	170	179	Ω
R_tR_s	8.0×10^4	5.5×10^4	3.9×10^4	Ω^2
$^*E_t$ = 1 MV/m				

*from S. De Silva, JLEIC Collaboration Meeting 5th – 7th Oct 2016

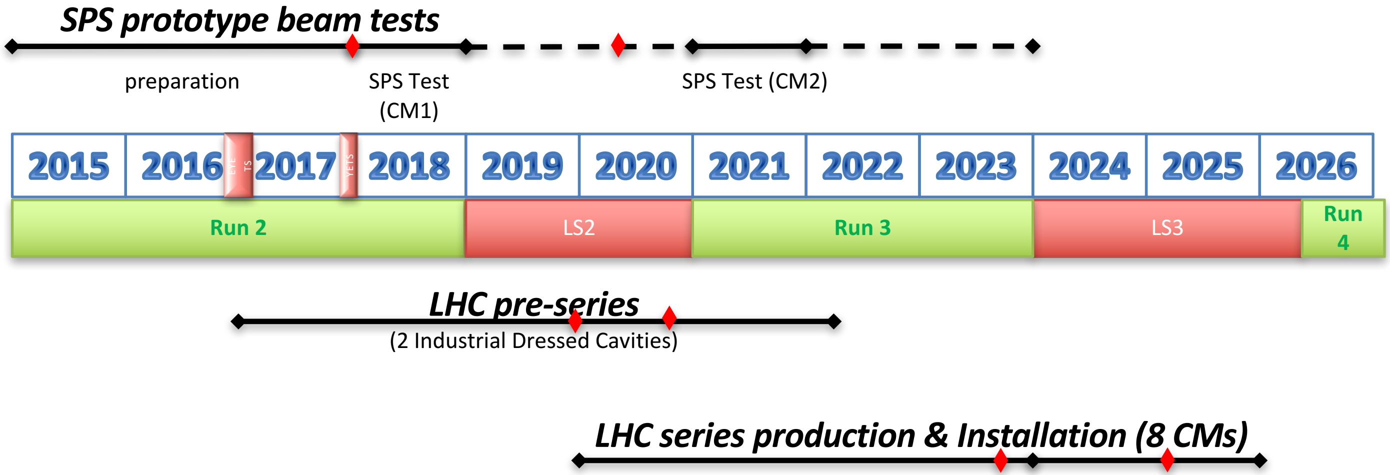
Example Designs (400 MHz)

R. Calaga, Chamonix '12

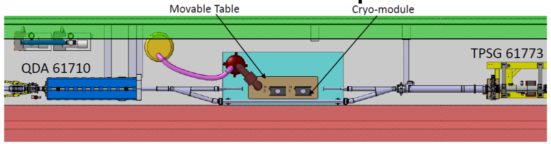


Exotic zoo of crab cavities developed in about 4 years (BNL, CERN, CI-JLAB, FNAL, KEK, ODU/JLAB, SLAC)
Three cavities remaining after down-selection.

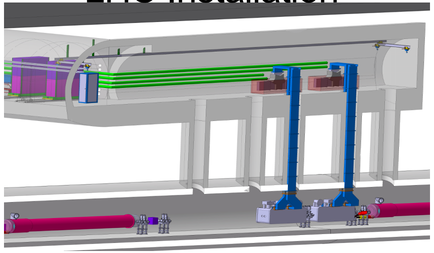
WP4 Planning



SPS Test Setup



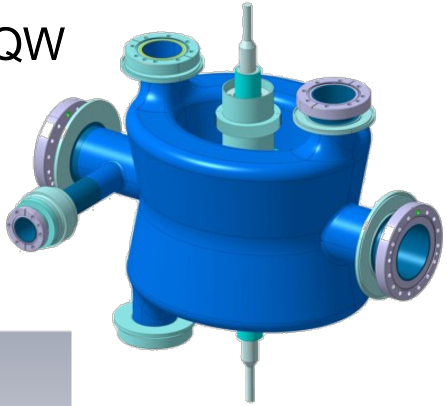
LHC Installation



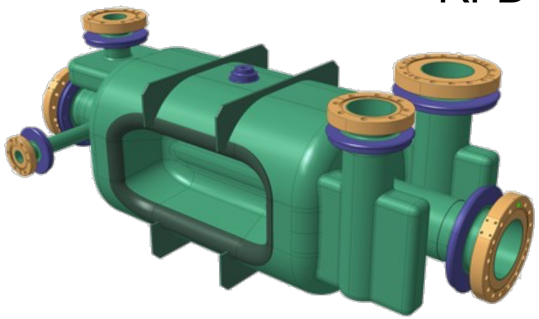
*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

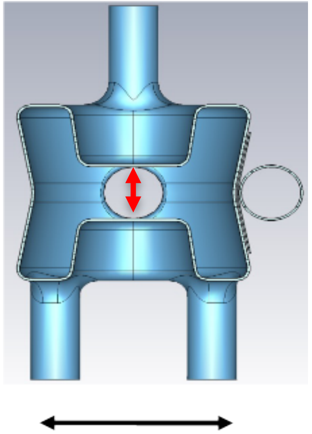
SPS Cavities, 2K Volume

DQW



RFD



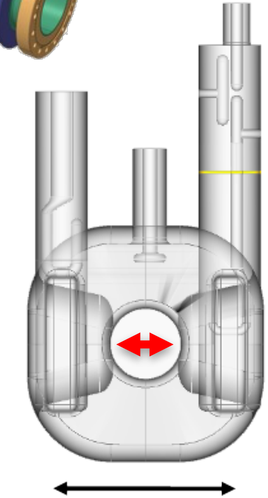


280 mm

Bulk Nb cavities, Dipolar symmetry

$V_T = 3.4\ \mathrm{MV}\ (E_p, B_p \leq 40\ \mathrm{MV/m}, 70\ \mathrm{mT})$
Stored energy $\sim 10 - 12\ \mathrm{J}$

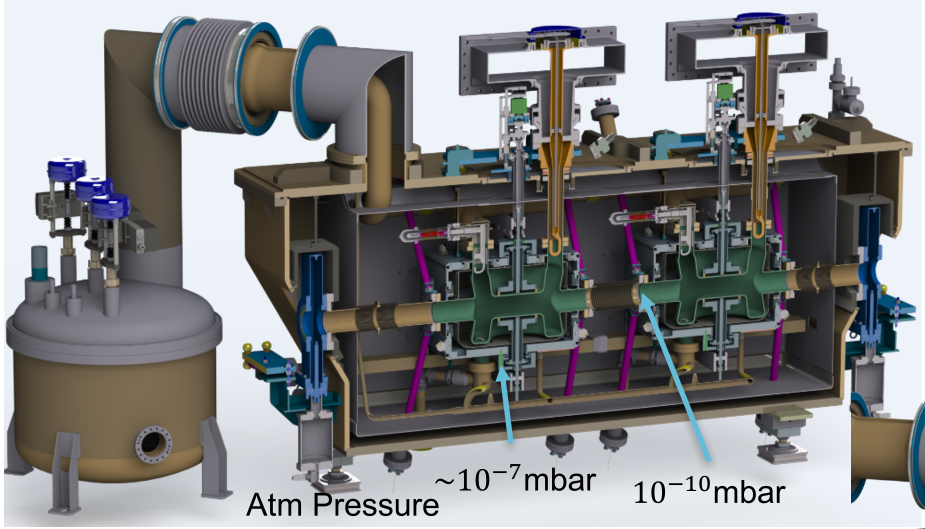
CERN insourced DQW production Nov 2015



281 mm

*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016

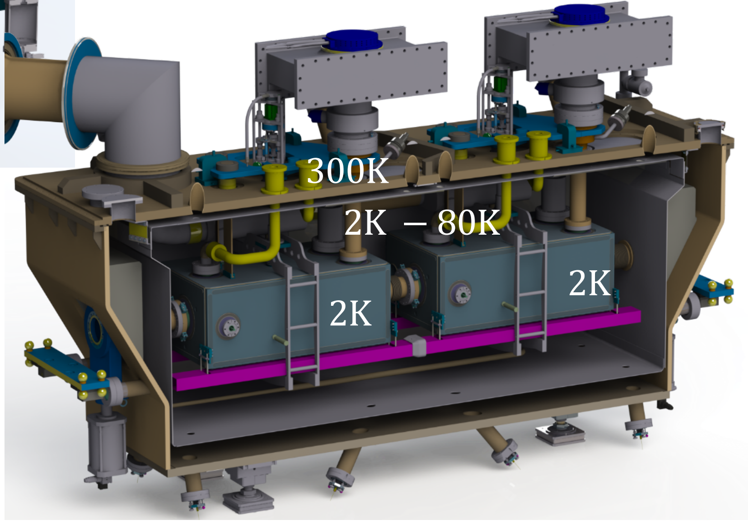
Prototype Cryomodules



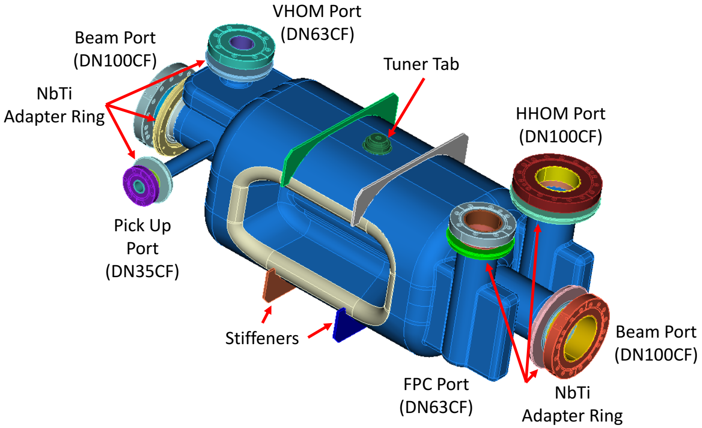
*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016

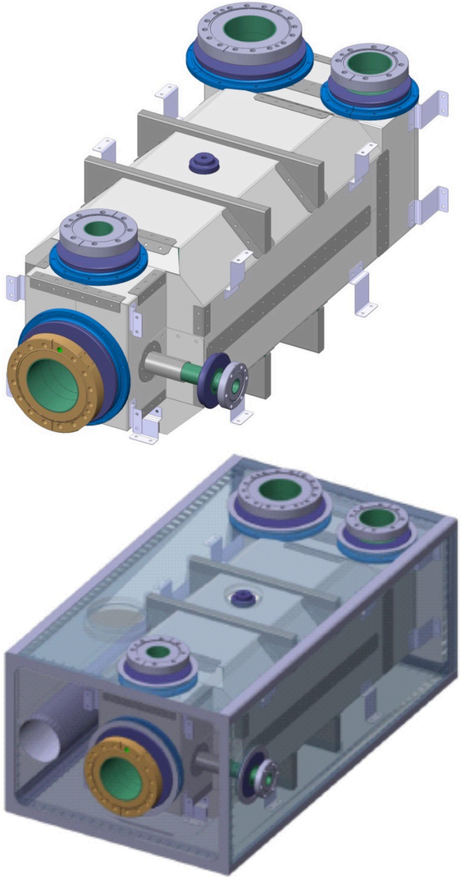
Vertical crossing for ATLAS, first one to go to SPS 2018

Horizontal crossing for CMS Cavities starting 2017



Design and Engineering of Prototypes

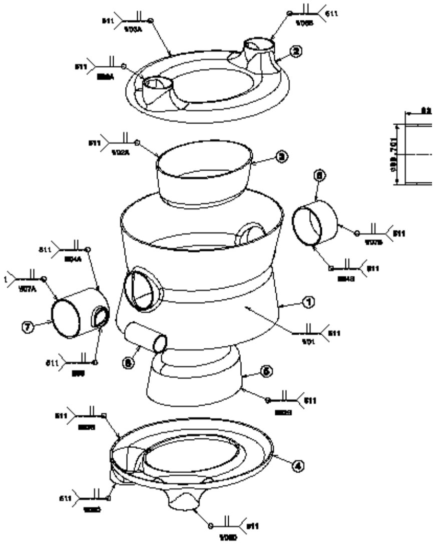




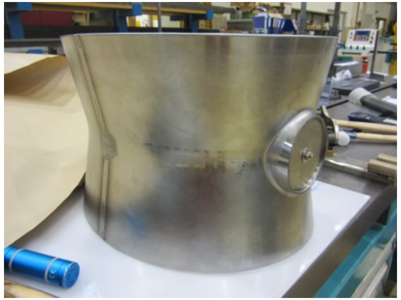
*from S. De Silva, JLEIC Collaboration Meeting 5th – 7th Oct 2016

SPS-DQW Cavity Fabrication

- First CERN cavity frequency trimming last week

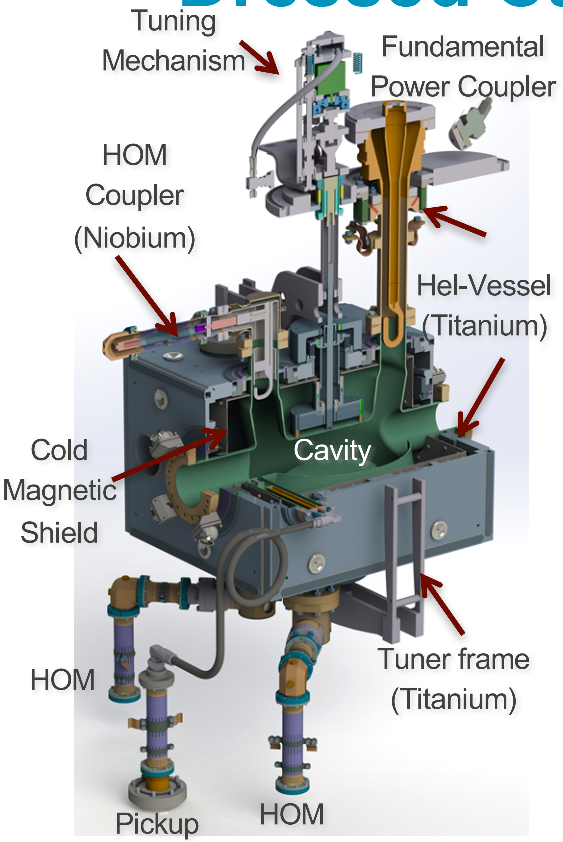


*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016



Cavity I cold test mid-Feb 2017 (Cavity 2 in early March)

Dressed Cavities (2K volume)



Main Mechanical interfaces:

- He-vessel: Bolted-welded concept
- Cold magnetic shield
- Tuner: Sym. tuning with warm actuation
- Three point support + alignment system

Main RF interfaces

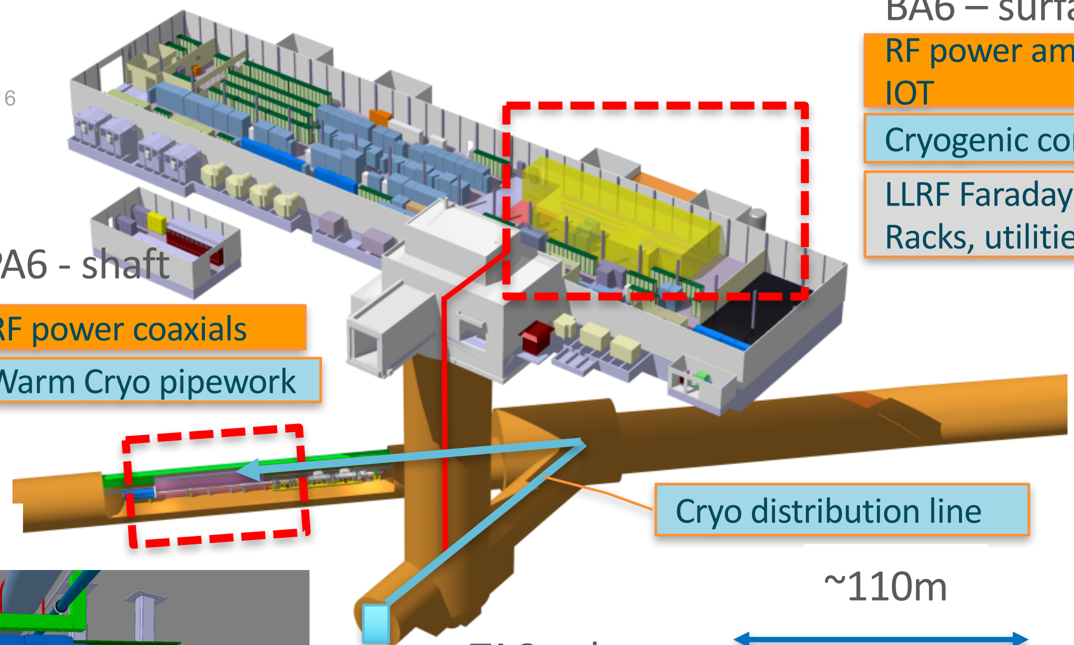
- 1 FPC: Single ceramic coaxial line
- 3 HOMs: Two stage filter, coaxial
- 1 PU: Cu-Nb for field probe + HOM

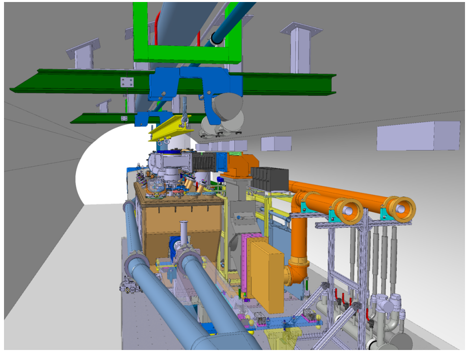
*from R. Calaga 6th HL-LHC Collaboration Meeting Nov 2016

Similar concept for RFD with different HOM interfaces

System architecture in SPS point 6

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

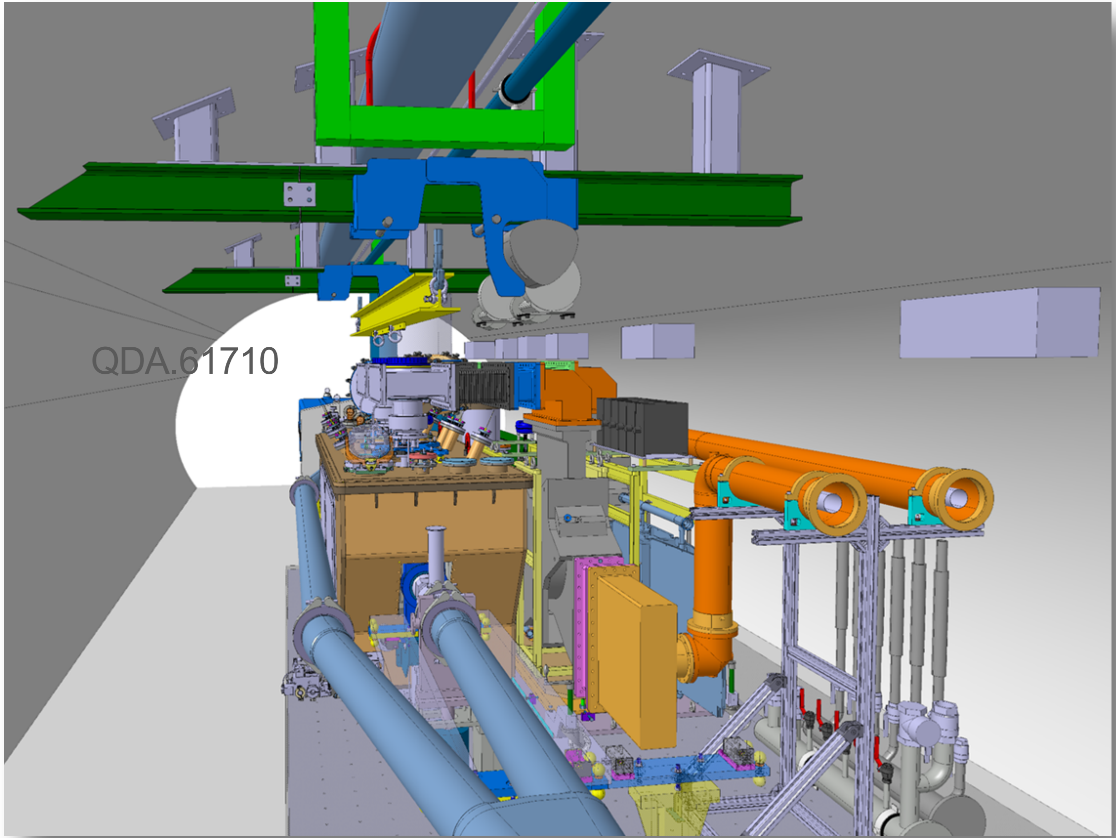




HL-LHC CC SPS test stand in 2016

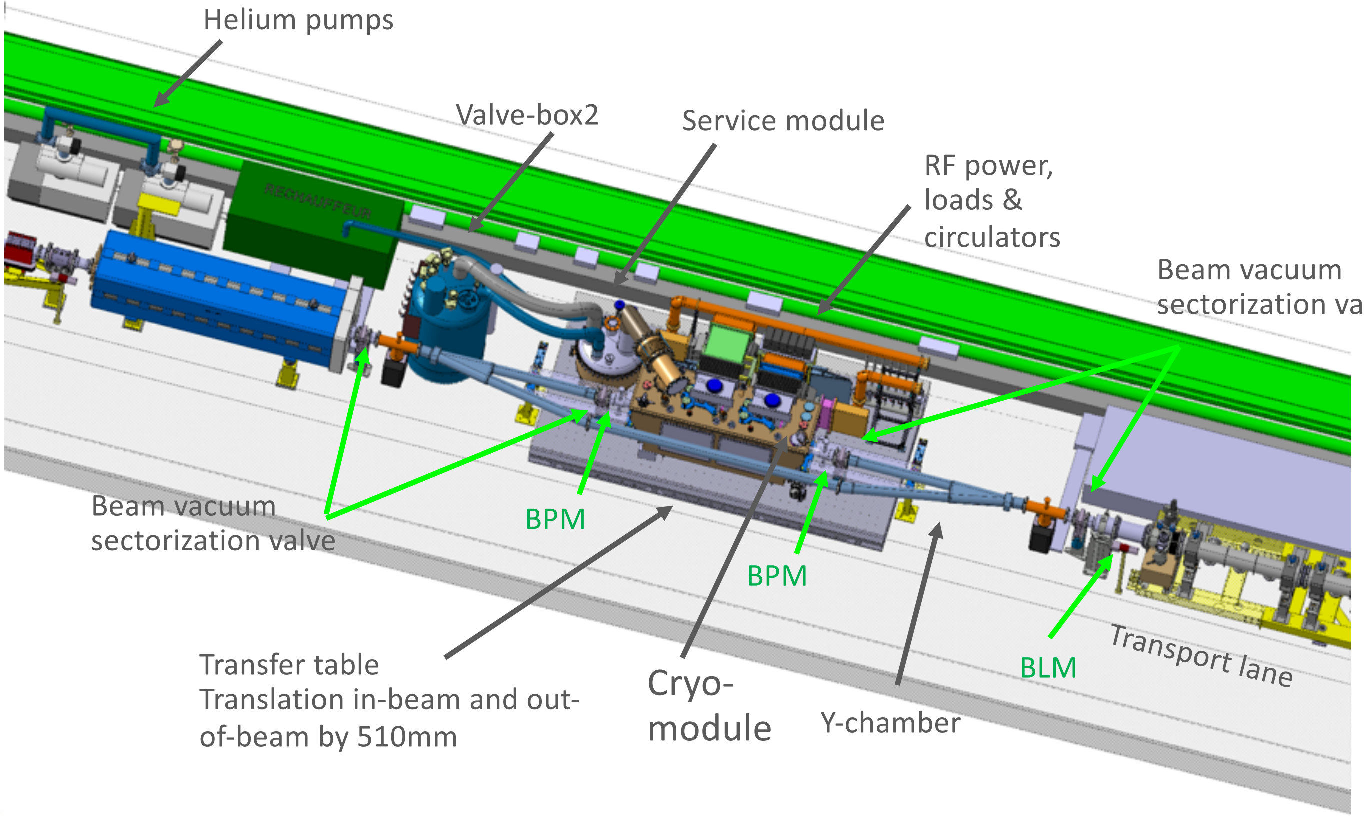
*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

HL-LHC CC SPS test stand in 2018



*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

HL-LHC CC SPS test stand layout



*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

SPS – Machine protection

The motorized transfer table supports the CCCM and proximity ancillaries

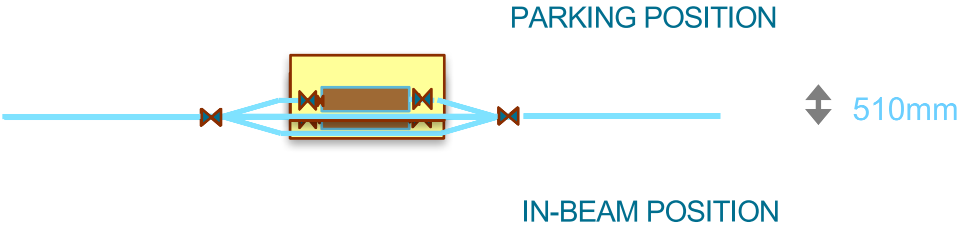


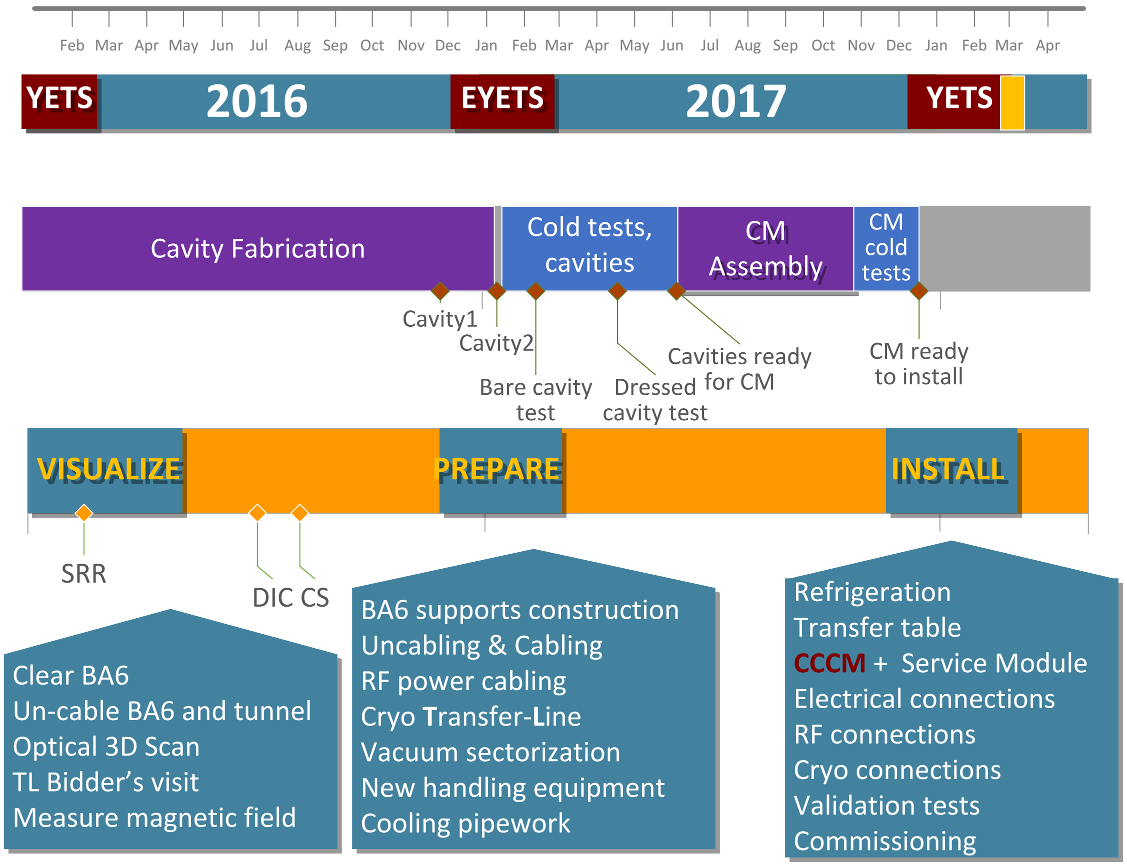
Table movement is interlocked by Access VETO in SPS and by Valves closed → Mitigation of the risk of cryogenic hazard

Table movement interlocks beam by sector valve closure

Table position interlocks beam and extraction → SPS-ring BIS and EXTR 1 BIS

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

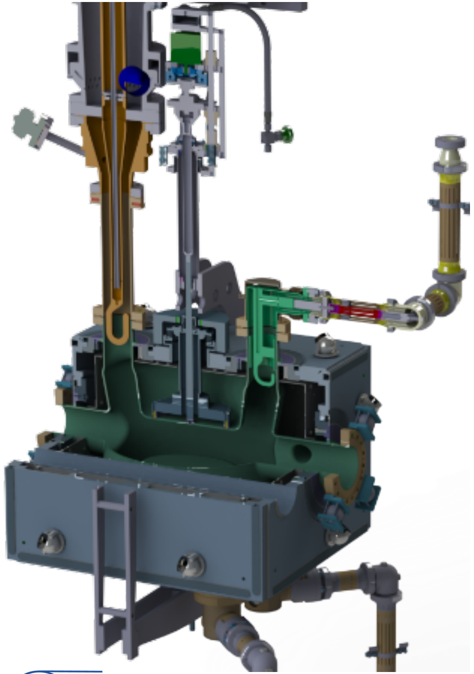
SPS Installation Master plan

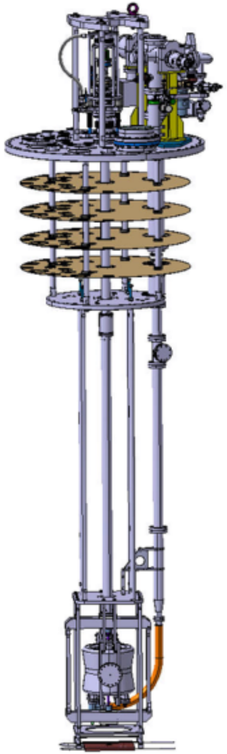


*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

Tuner Mockup Vs Cryomodule

SPS-Series



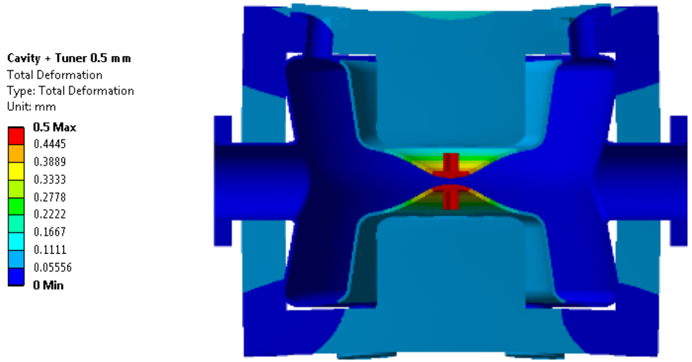


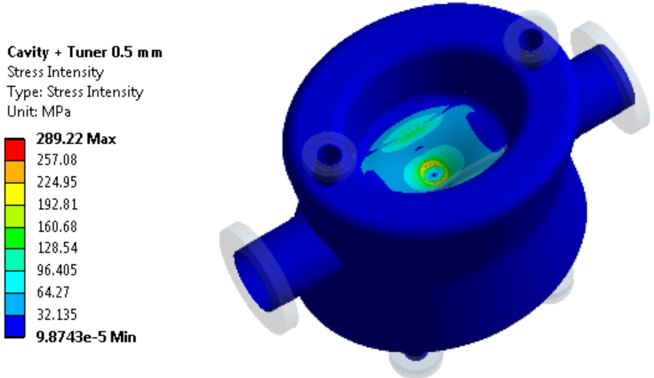
Proof-of-Principle

DQW Proof-of-Principle

J. Swiesek and K. Artoos

- Calculations Norbert Kuder for 0.5 mm displacement on each plate. Maximum stress intensity: 289 MPa
- Elastic limit Nb with 1.5 safety factor is 320 MPa at 2 K (Material properties for mechanical and thermal analysis, EDMS 1530740)
- Since rigidification by welds are not in the model + other factors like Nb thickness variation, etc.:
    - **Maximum 0.5 mm motor displacement for the DQW-PoP tuner test**



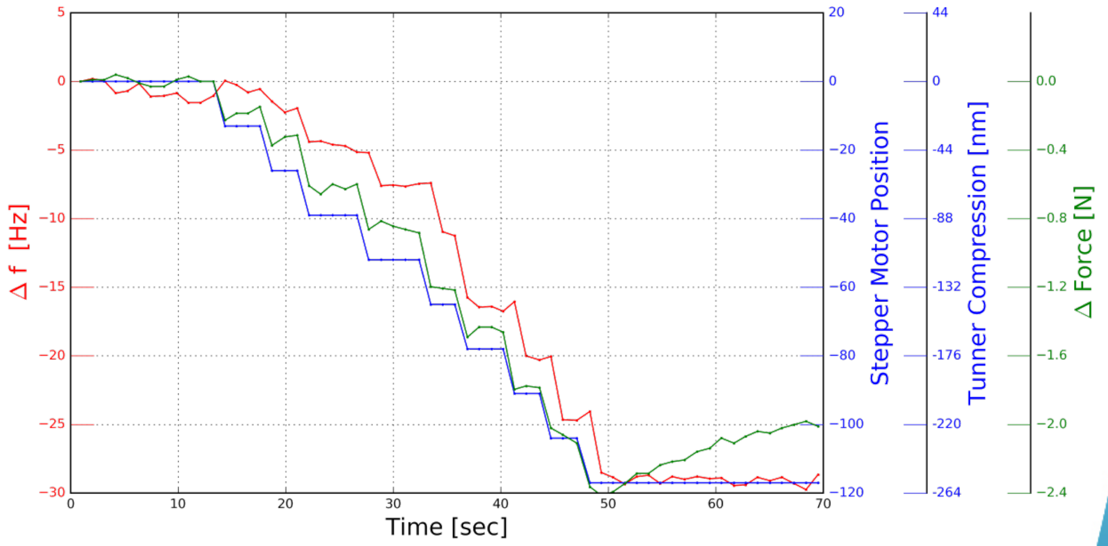


SM18 Tuner Mockup Setup

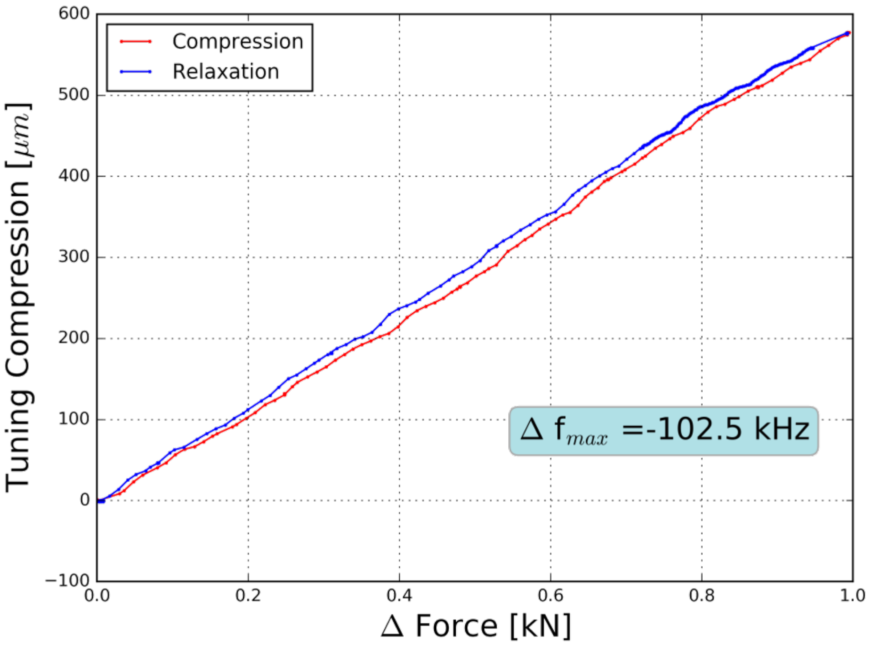
- **Test Stand**
  - New test stand commissioned to allow the tuner test configuration
  - New user interface deployed
    - RF testing
    - Motor controls
- **Diagnostics**
  - Temperature mapping
  - 3 axis B-flux gauges
  - 2^{nd} Sound detection
  - Strain gauge

Tuner Small Steps

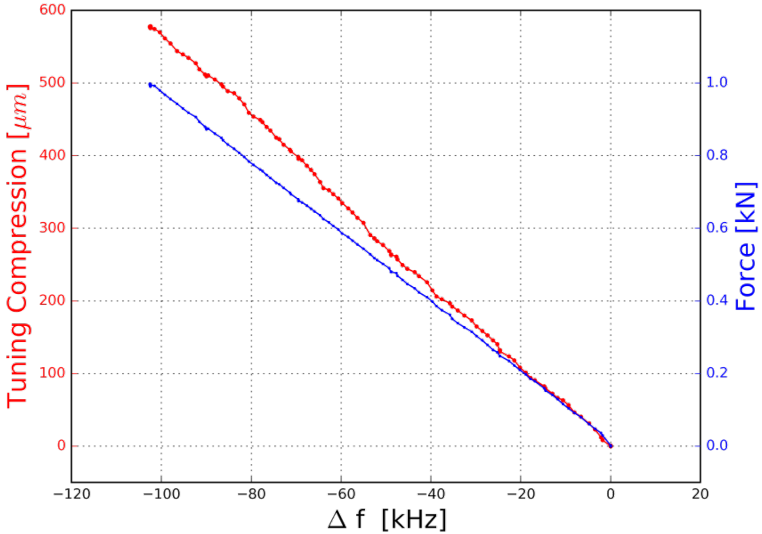
- Moving 116 steps
  - ~256 nm displacement
  - Total freq. shift ~29 Hz
  - Average measure of 2.2 nm/step
- From large freq. excursions
  - ${}^{\Delta f}/_{\Delta y}$ ≈180 kHz/mm



Maximum Tuning Excursion

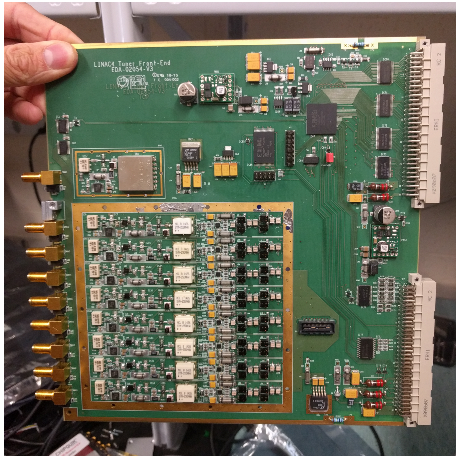


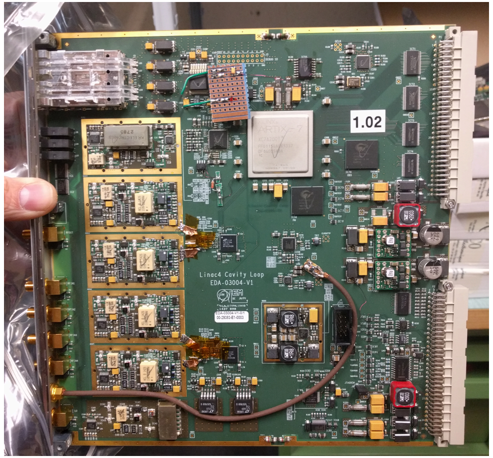
- After fixing end stops and motor slippage

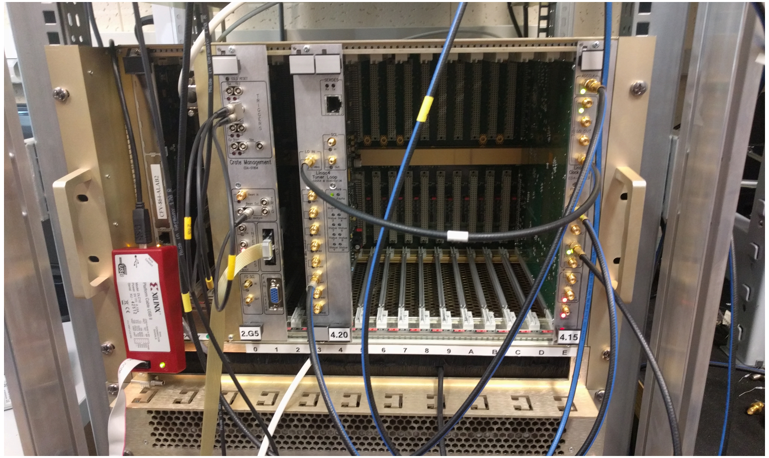


Following: CC LLRF + Tuner

- Design evolving from the existing Linac 4 cards/crates
  - A few firmware changes are needed:
    - Change from 352.2 MHz to 400.8 MHz, sampling, etc.
    - Change from pulsed to CW operation, etc.





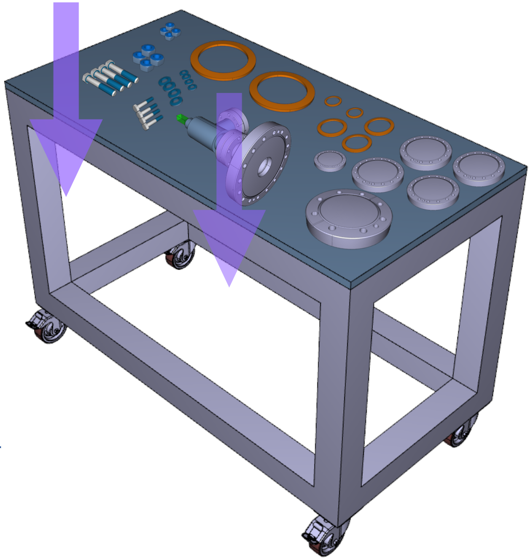


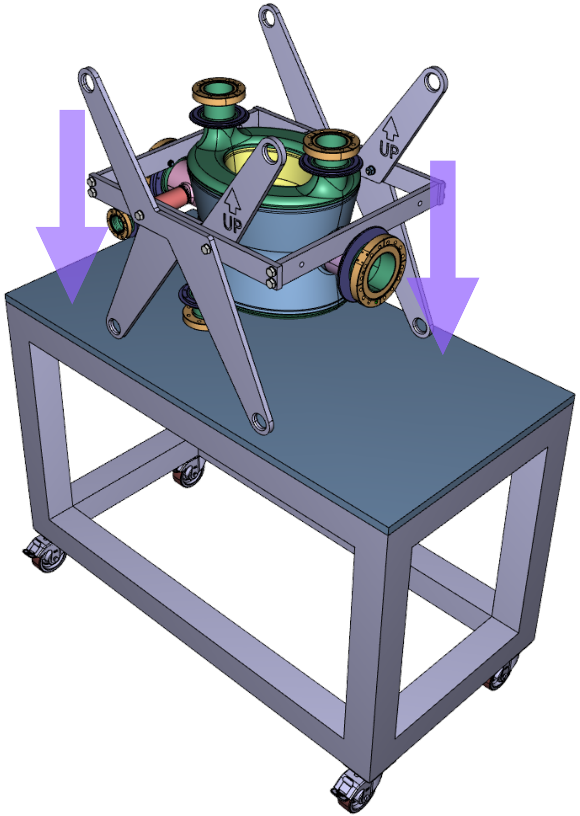
P. Baudrenhien, B. Kremel, J. Simonin and N. Stapley

Clean Room Assembly (Bare Cavity)

- Clean assembly
  - Parts and pre-assemblies ready
  - Under laminar flow
  - Systematic sequence

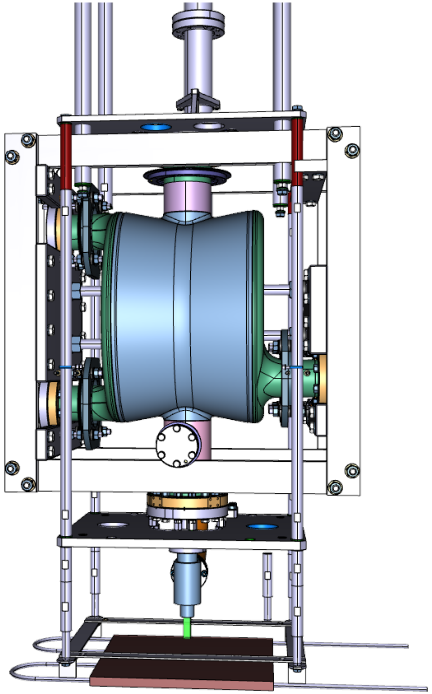
ISO4

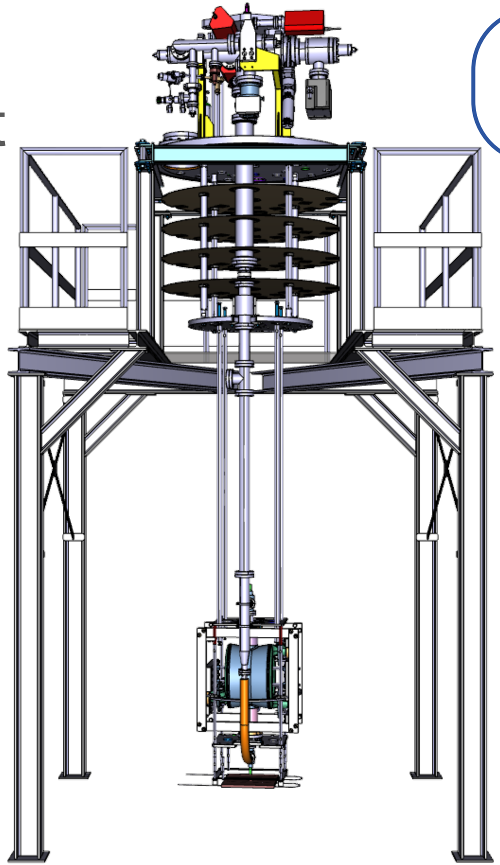




Insert Installation (Bare Cavity)

- Remove from chariot
- Mechanically mount onto insert



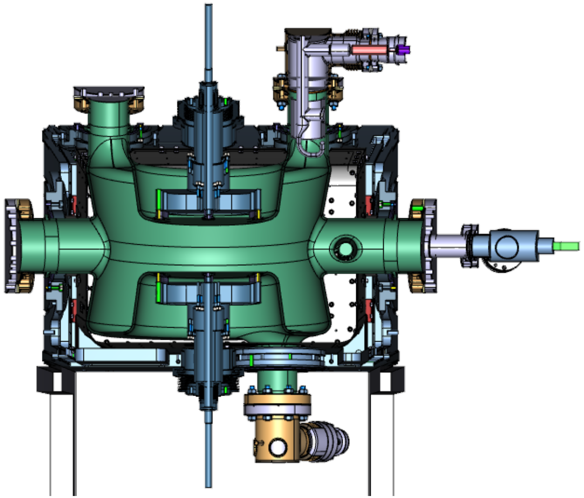


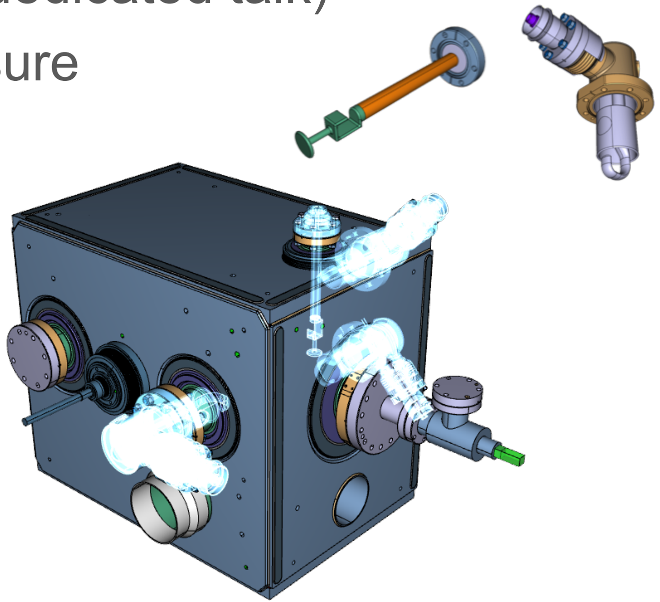
SM18 RF-zone

Clean Room Assembly (Part. Dressed Cavity)

ISO4

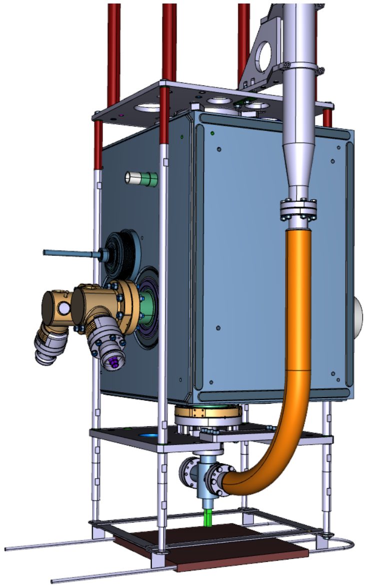
- Cavity + He tank is moved to ISO4
- Mounting of HOMs couplers and RF field antenna
  - Done by E. Montesinos' team (see dedicated talk)
  - One-by-one with nitrogen overpressure



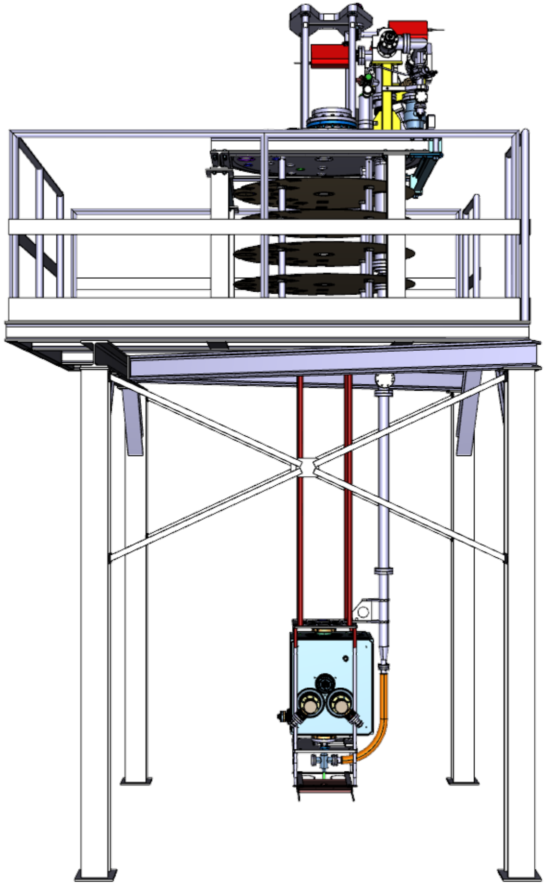


Part. Dressed Cavity Insert Installation

- Mounting into insert
  - Vacuum line connection and leak check procedure similar to bare cavity



SM18
RF-zone



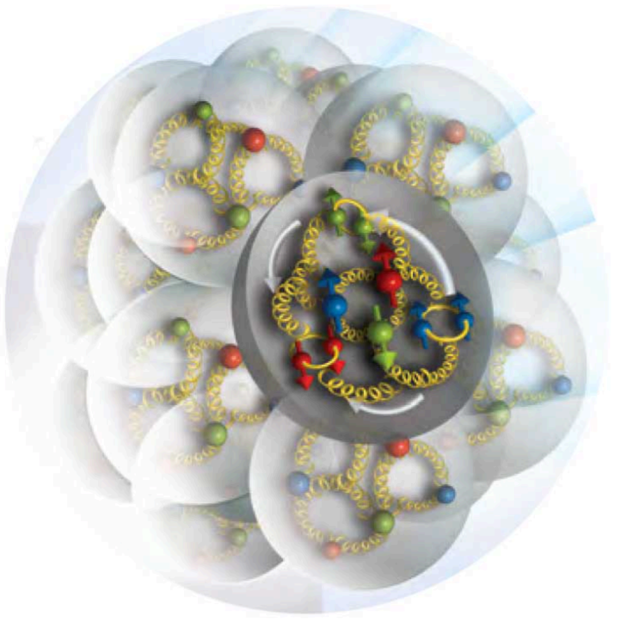
Summary

- Lots of studies done and undergoing:
  - Machine Integration
  - Machine Protection
  - and some others still missing…
- Great efforts at CERN for infrastructure and tooling
- Insourcing of cavity fabrication has been an important investment for CERN
- Very tight schedule with a very promising added value
- Synergy of the CC program between JLEIC and CERN

Thank you

Acknowledgement, credits: R. Calaga, O. Capatina, M. Garlasche, A. Macpherson, K. Schirm, G. Vandoni, R. Thomas, K. Artoos, J. Swiesek, N. Shipman, I. Ben-Svi, S. Verdu, S. De Silva, J. Delayen, H. Park, V. Morozov, …

Jefferson Lab - EIC

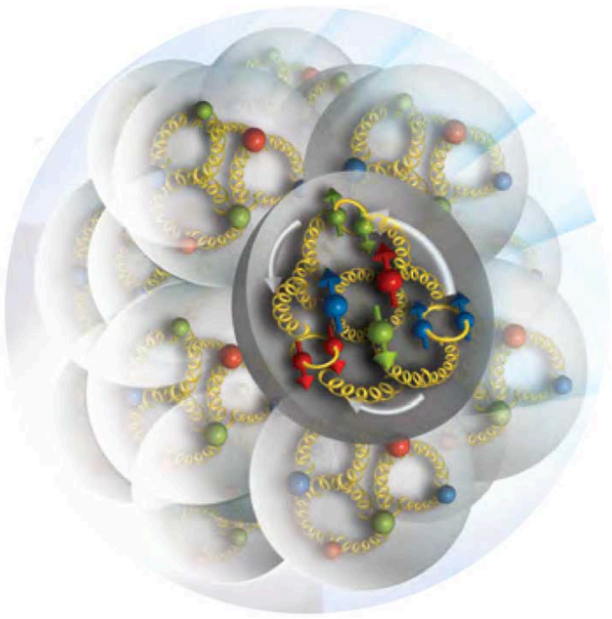


- Understanding the nucleon, nuclear structure and associated dynamics

- Probe the nucleon
  - many-body regime
    - $x \approx 0.005$ at large Q^2
- Probe the nuclei
  - N-N and multi-N interaction regime
    - at large Q^2
- Extend of QCD
  - Saturation
  - Jets in cold matter

*from R. Yoshida, JLEIC Collaboration Meeting 5th – 7th Oct 2016

Jefferson Lab - EIC



*from R. Yoshida, JLEIC Collaboration Meeting 5th – 7th Oct 2016

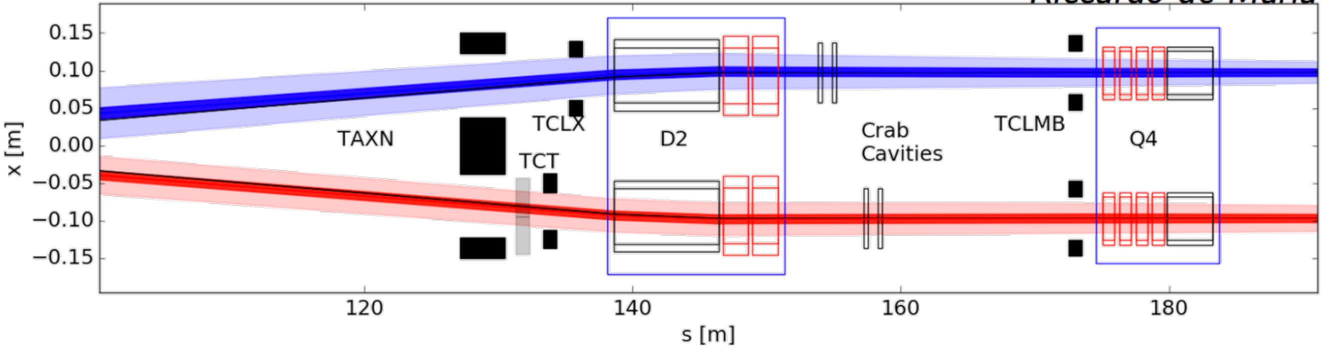
- Non-Perturbative Quantum Chromodynamics (+TR)
  - Jefferson Lab 12 GeV
    - Quantitative understanding of DIS processes
- Perturbative Quantum Chromodynamics (pQCD)
  - Jefferson Lab EIC
    - Full picture of nucleons and nuclei
    - Origin of mass, spin, nuclear forces,…

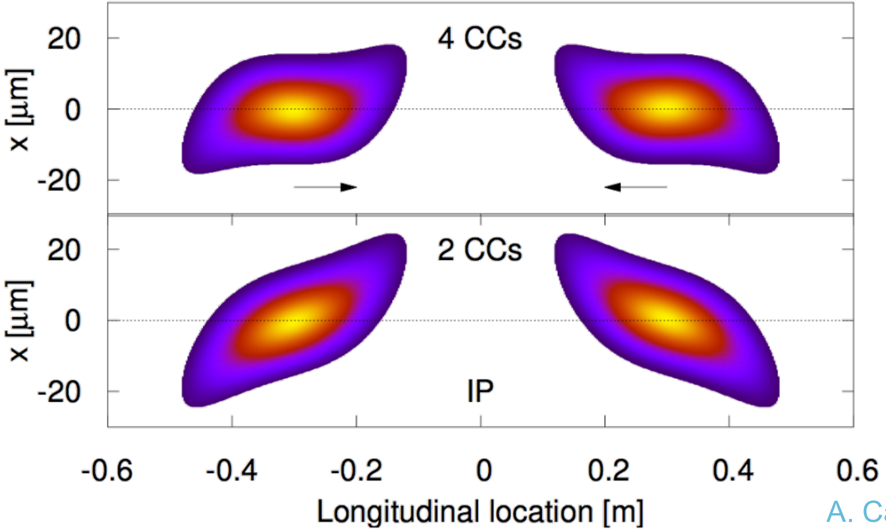
LHC 2016 Run

Parameter	Chamonix 16	Actual - July 16 - BCMS	
Energy [TeV]	6.5	6.5	
Bunch spacing	25 ns	25 ns	288 bunches per injection following TDI replacement
β* (1/2/5/8) [m]	0.4 / 10 / 0.4 / 3	0.4 / 10 / 0.4 / 3	Tested in 2015 - 0.5 m also an option
Ext. half X-angle (1/2/5/8) [μrad]	-185 / 200 / 185 / -250	-185 / 200 / 185 / -250	10 sigma in 1&5 assuming 3.75 micron emittance
Number of colliding bunches (1/5)	2736 nominal 25 ns	2076	Limited by SPS dump to 96 bpi as of July 16
Bunch population	1.2e11	1.18e11	
Emittance into Stable Beams [μm]	3.5	2.6	
Bunch length [ns] - 4 sigma	1.25	1.05	Start of fill
Peak Luminosity (L0) [cm-2s-1]	1.1e34	1.1e34	BCMS could give around 1.4e34
Peak mean pile-up (*inel xsection 80 mb*)	29	39	cf. ~40 with BCMS

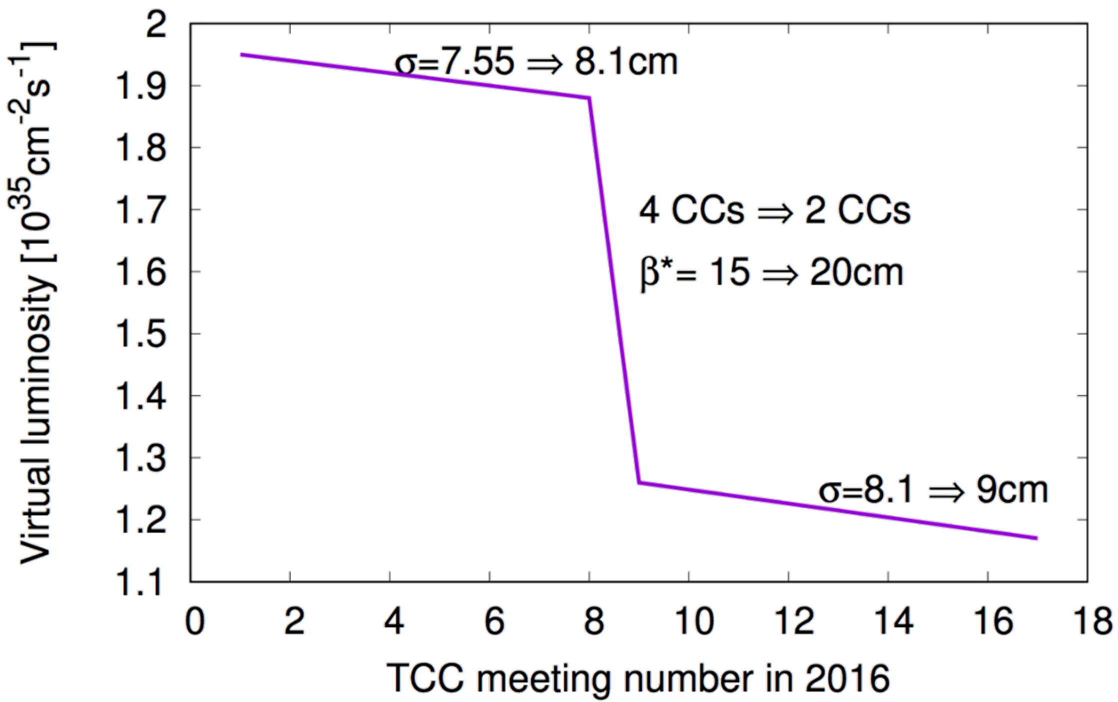
Number of crab cavities halved

Riccardo de Maria



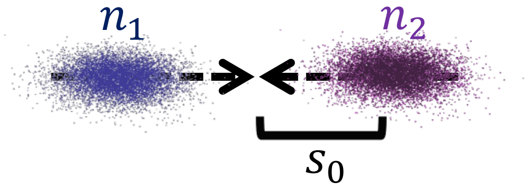


HL-LHC virtual luminosity in 2016



TCC meetings: https://indico.cern.ch/category/7361/

Luminosity: A Primer



- Per bunch crossing

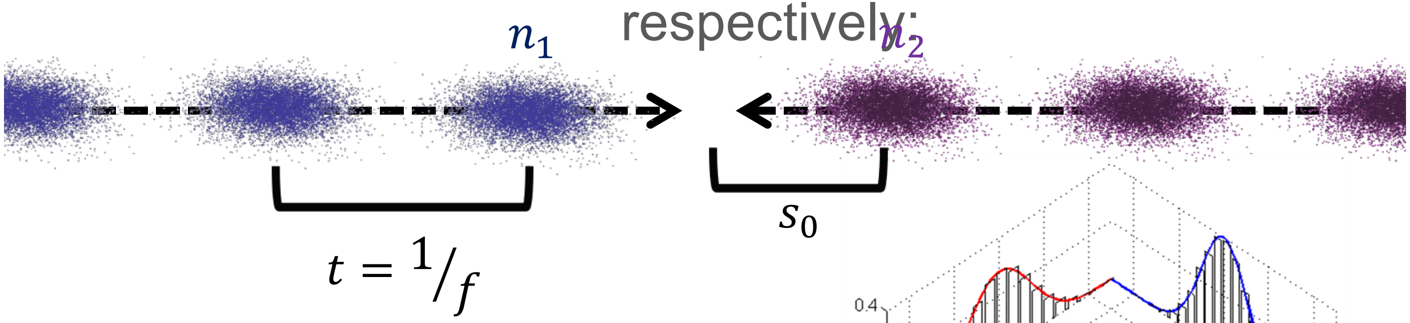
$$\mathcal{L} = K \cdot n_1 n_2 \cdot \iiint_{-\infty}^{\infty} dx dy ds ds_0 [\rho_1(x, y, s, -s_0) \cdot \rho_2 (x, y, s, s_0)]$$

- Where $s_0 = ct$
- And K is the kinematic factor $\sqrt{(\vec{v}_1 - \vec{v}_2)^2 - (\vec{v}_1 \times \vec{v}_2)^2 / c^2}$
- Head-on collisions $(\vec{v}_1 = -\vec{v}_2)$, then $K = 2$
- For uncorrelated distributions:

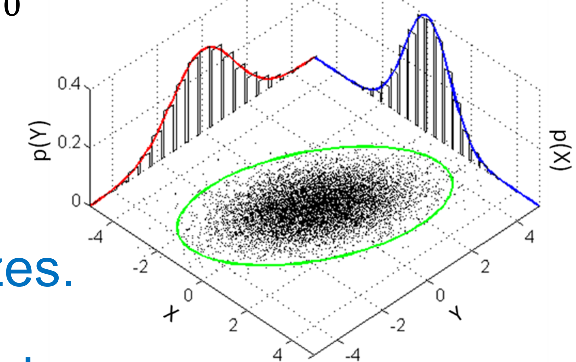
$$\rho(x, y, s, s_0) = \rho_x(x) \rho_y(y) \rho_s(s \pm s_0)$$

Luminosity: A Primer

- For two bunches with n_1 and n_2 particles respectively;



- Where $\sigma_{x/y}$ are the rms horizontal/vertical beam sizes.
- No offset and head-on collision.



https://en.wikipedia.org/wiki/Multivariate_normal_distribution

Luminosity: A Primer

- For two beams:

$$\mathcal{L} = 2 \cdot n_1 n_2 \cdot f \cdot N_b \cdot \iiint_{-\infty}^{\infty} dxdydsds_0 [$$

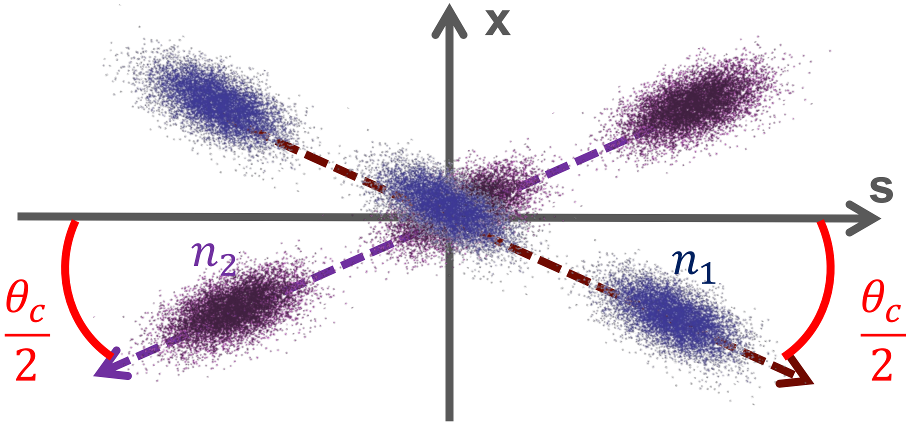
$$\rho_{1x}(x)\rho_{1y}(y)\rho_{1s}(s - s_0) \cdot \rho_{2x}(x)\rho_{2y}(y)\rho_{2s}(s + s_0)]$$

- The Gaussian distributions can be written:

$$\rho_{iu}(u) = \frac{1}{\sigma_{iu}\sqrt{2\pi}} e^{\left(-\frac{u^2}{2\sigma_{iu}{}^2}\right)}, \;\; \rho_s(s \pm s_0) = \frac{1}{\sigma_s\sqrt{2\pi}} e^{\left(-\frac{(s \pm s_0)^2}{2\sigma_s{}^2}\right)};$$

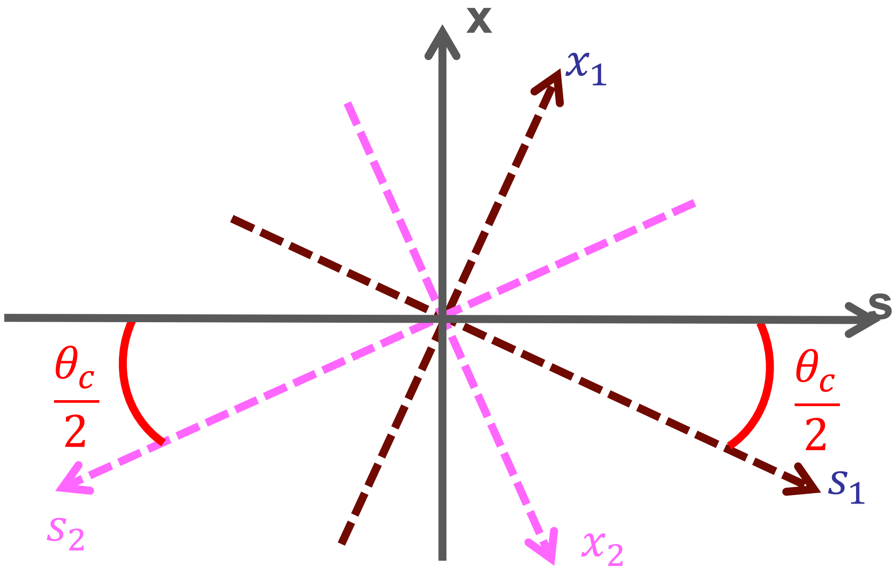
where $u = x, y$ and $i = 1{,}2$ indicates the bunch number

Crossing Angle



- Using rotated reference frames per beam
  - change of coordinates
  - rewrite Gaussian distributions
  - compute the new Gaussian integrals

Crossing Angle



- $x_1 = x\cos\frac{\theta_c}{2} + s\sin\frac{\theta_c}{2}\,,\; s_1 = s\cos\frac{\theta_c}{2} - x\sin\frac{\theta_c}{2}\,.$
- $x_2 = -x\cos\frac{\theta_c}{2} + s\sin\frac{\theta_c}{2}\,,\; s_2 = -s\cos\frac{\theta_c}{2} - x\sin\frac{\theta_c}{2}\,.$

Luminosity + Crossing Angle

- For two beams:

$$\mathcal{L} = 2 \cdot n_1 n_2 \cdot f \cdot N_b \cdot \iiint_{-\infty}^{\infty} dxdydsds_0 [$$

$$\rho_{1x}(x_1)\rho_{1y}(y_1)\rho_{1s}(s_1 - s_0) \cdot \rho_{2x}(x_2)\rho_{2y}(y_2)\rho_{2s}(s_2 + s_0)]$$

- Now we will use:

$$\int_{-\infty}^{\infty} dt e^{-(at^2+bt+c)} = \sqrt{\frac{\pi}{a}} \cdot e^{\frac{b^2-ac}{a}}$$

Luminosity + Crossing Angle

- Some more approximations since ${}^{\theta_c}/_2$ is small:

$$\sin {}^{\theta_c}/_2 \sim \tan {}^{\theta_c}/_2 \sim {}^{\theta_c}/_2 \,;$$

discarding $\begin{cases} {\sigma_x}^k \sin^l {}^{\theta_c}/_2 \\ x^k \sin^l {}^{\theta_c}/_2 \end{cases} ;\ \forall\, k + l \geq 4$

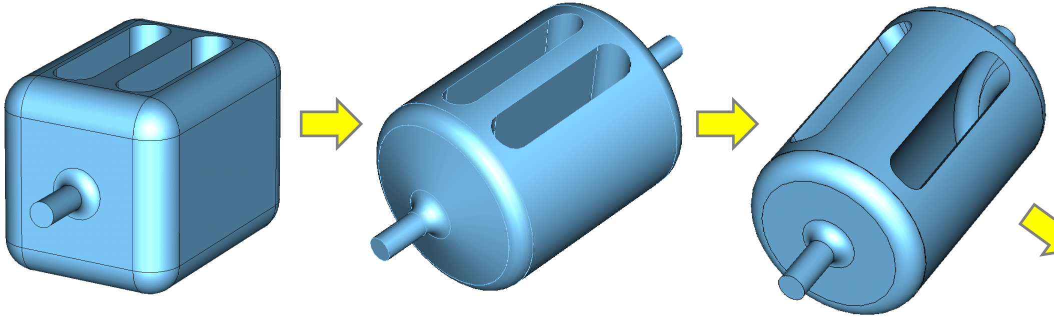
- And so the result is slightly different:

$$\mathcal{L} = \frac{n_1 n_2 f N_b}{4\pi\epsilon\sqrt{\beta_x^* \beta_y^*}} \cdot \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\frac{\theta_c}{2}\right)^2}}$$

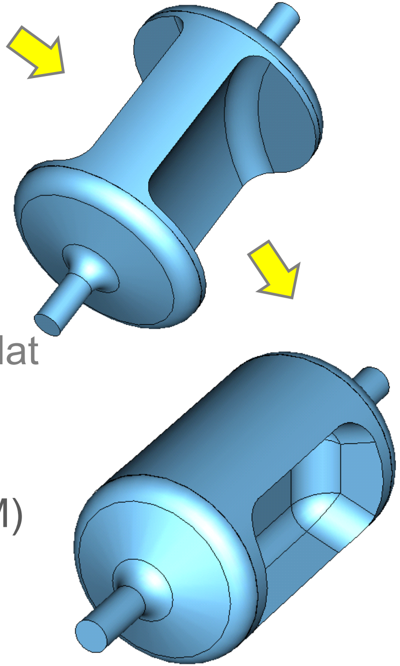
HiLumi HL-LHC PROJECT

CERN

The RF Dipole Family Tree

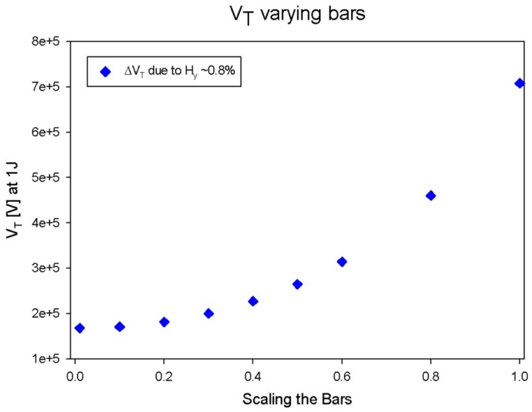


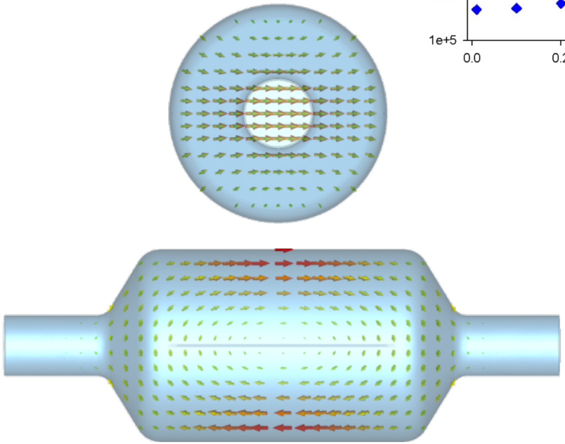
*from S. De Silva, ODU-JLab 2012.

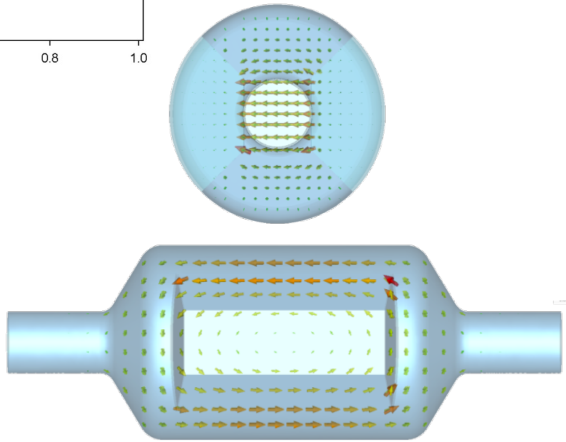


- Aspects of optimization
  - Lower and balanced peak surface fields
  - Stability of the design:
    - Cylindrical shape is preferred to reduce flat surfaces.
  - Curved end plates for cleaning the cavity.
  - Wider separation in Higher Order Mode (HOM) spectrum.
  - Multipacting

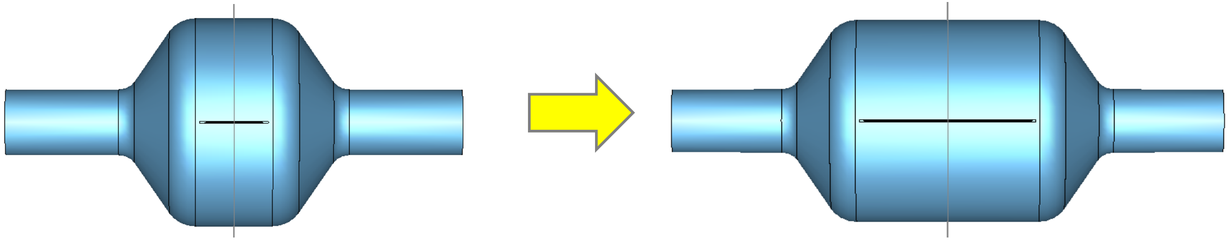
TE-Like Transverse Kick

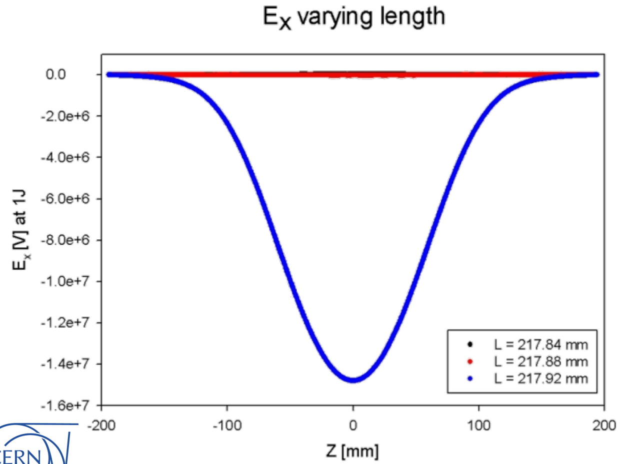


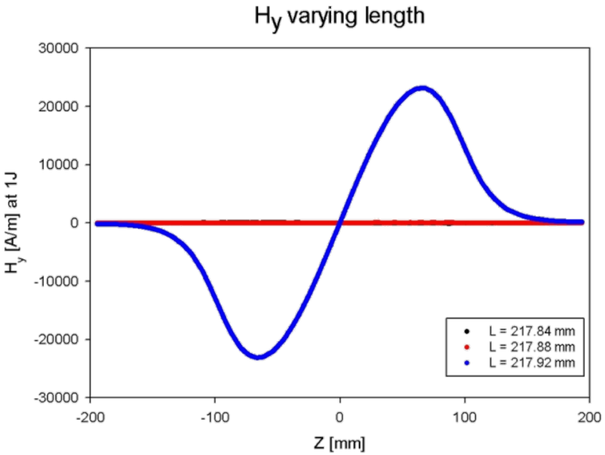




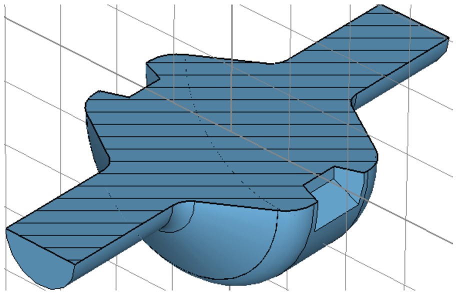
Accelerating to Deflecting

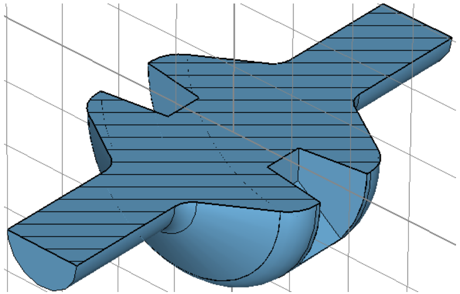


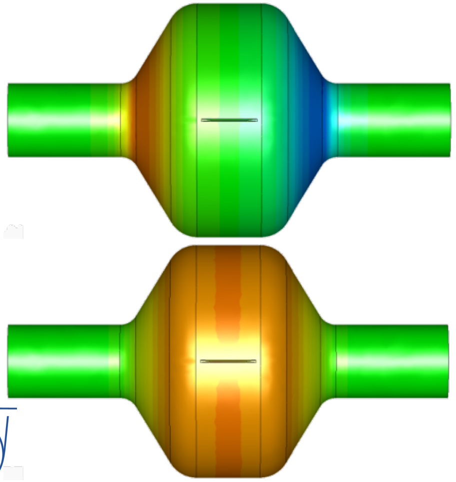




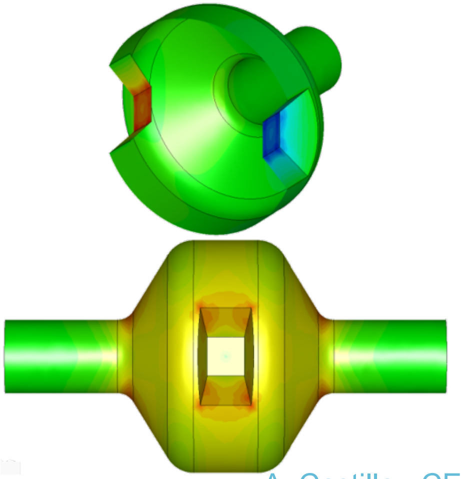
Accelerating to Deflecting (2)





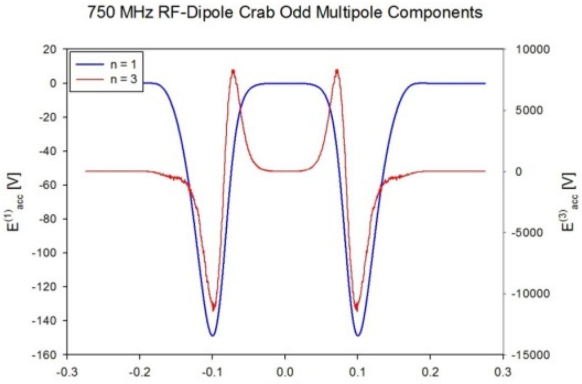


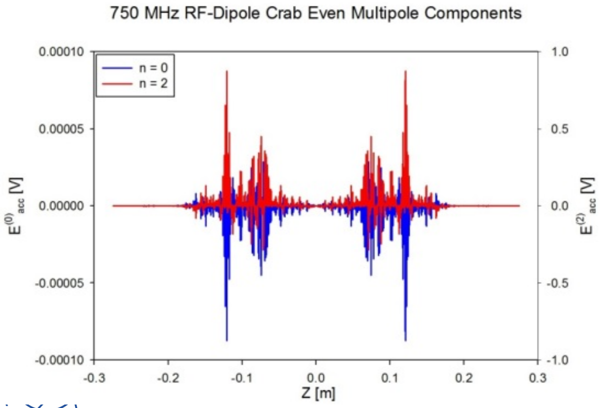
Electric Field

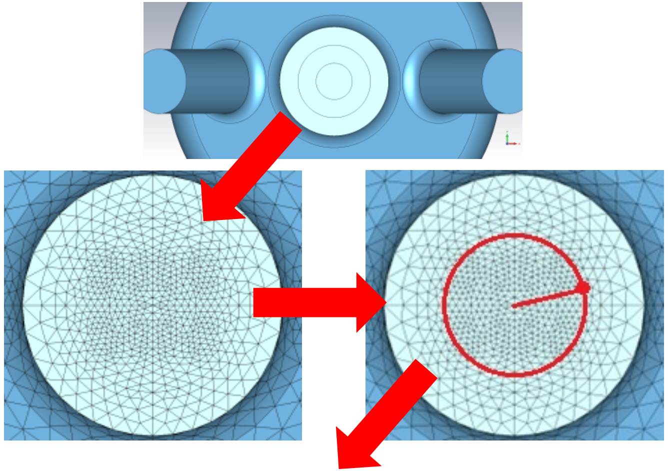


Magnetic Field

Multipole Expansion

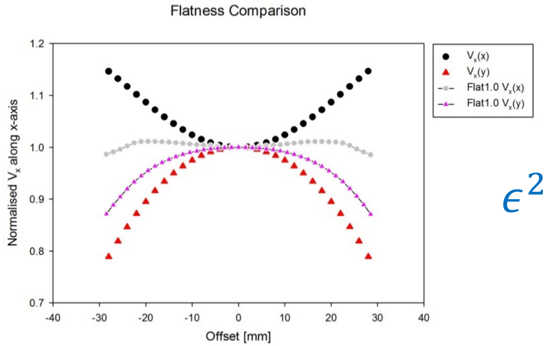






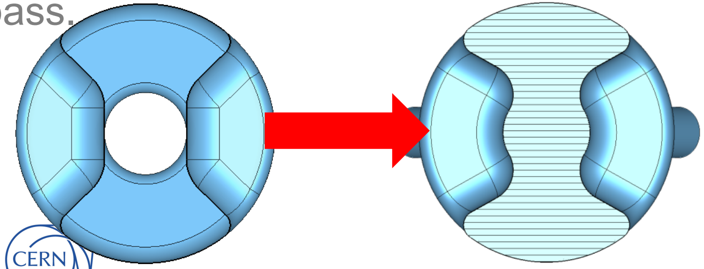
	750 MHz	Units
V_t	1.0	MV
b_1	3.3	mT m
b_2	0.0	mT
b_3	1.81	$(\times 10^2)$ mT/m
b_4	0.0	mT/m^2
b_5	-5.2	$(\times 10^5)$ mT/m^3

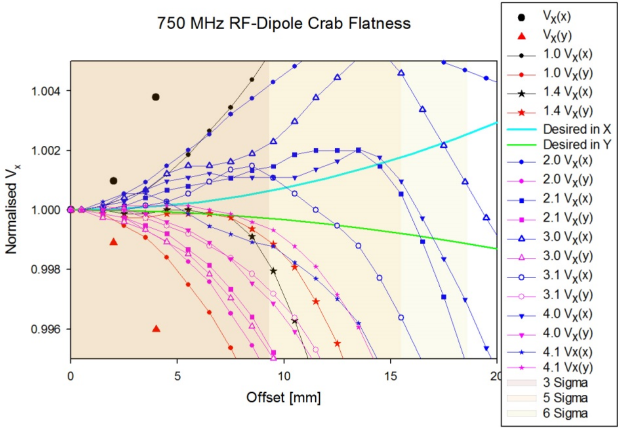
Field Flatness & Emittance



$$\epsilon^2{}_{n,rms} \equiv \epsilon^2{}_{0n,rms} + \frac{x^2{}_{0,rms}\left(\overline{\Delta p_x^2} - \overline{\Delta p_x}^2\right)}{m^2 c^2}$$

For a proton beam on axis coming with $\epsilon_{0n,rms}(y) = 0.07\mu m - rad$ then leaves with $\epsilon_{n,rms}(y) = 0.13\mu m - rad$ after 1 pass.





750 MHz MEIC-Crab Design Parameters

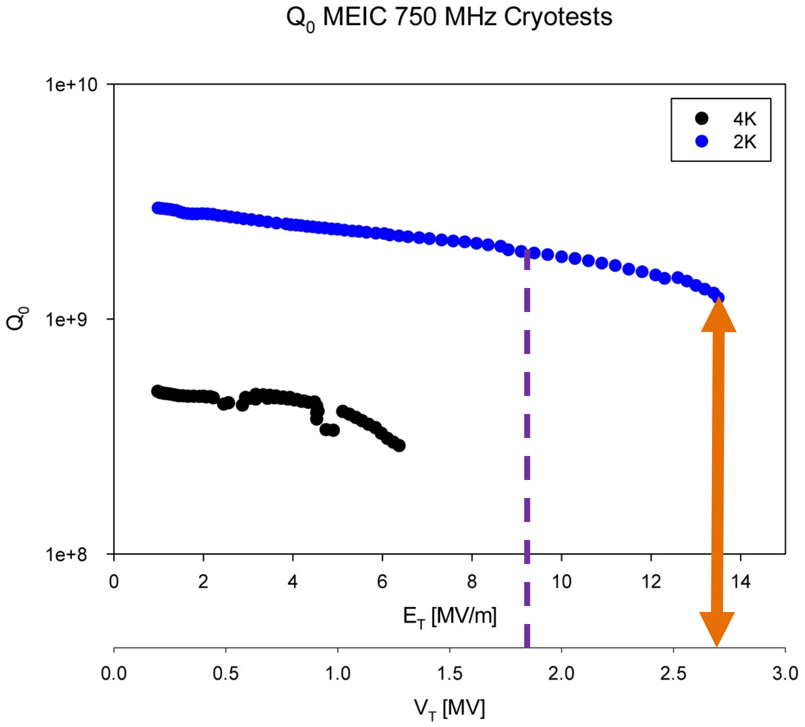
Parameter	MEIC RF-Dipole	Unit
Frequency of p-mode	750.1	MHz
λ/2 of p-mode	200.0	mm
Frequency of 0-mode	1350.6	MHz
Cavity length	549.3	mm
Cavity width	93.7	mm
Cavity height	93.7	mm
Bars length	200.0	mm
Bar Vertical Angle	45	deg
Bar Horizontal Angle	10.9	deg
Bars height	63.0	mm
Aperture diameter	60.0	mm
Deflecting voltage V_t *	0.2	MV
E_p *	4.45	MV/m
B_p *	9.31	mT
G	131.4	Ω
R_t/Q	124.15	Ω
$R_t R_s$	1.65 x 10^4	$Ω^2$

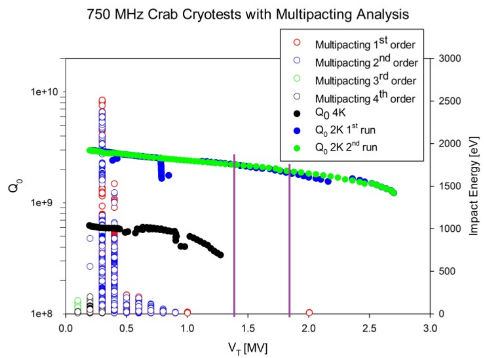
$$E_T^* = 1 \,{}^{MV}/_{m}$$

$$\frac{B_p}{E_p} \sim 2.1 \,{}^{mT}/_{(MV/m)}$$

$$E_T = \frac{V_T}{\lambda/2} \Rightarrow V_T^* = 0.2\, MV$$

750 MHz MEIC-Crab Test Results

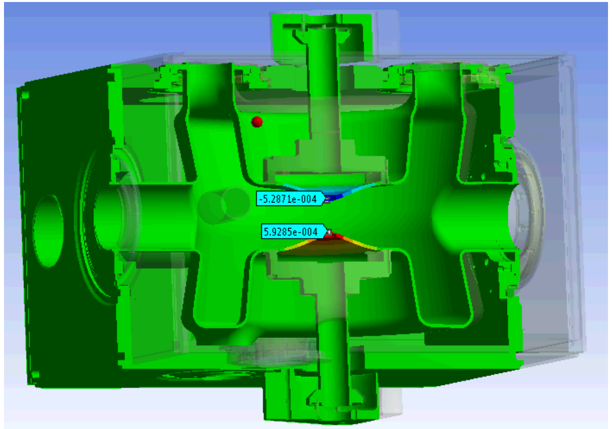




- Multipacting levels were easily processed at 1.99 K.
- Design requirement of <2 MV can be achieved with 1 cavity
- Achieved fields at 1.99 K
  - E_T = 13.5 MV/m
  - V_T = 2.7 MV
  - E_P = 60.08 MV/m
  - B_P = 125.69 mT

DQW SPS-Series

K. Artoos et al, for the Crab Cavities Cryomodule Review, Nov. 2015



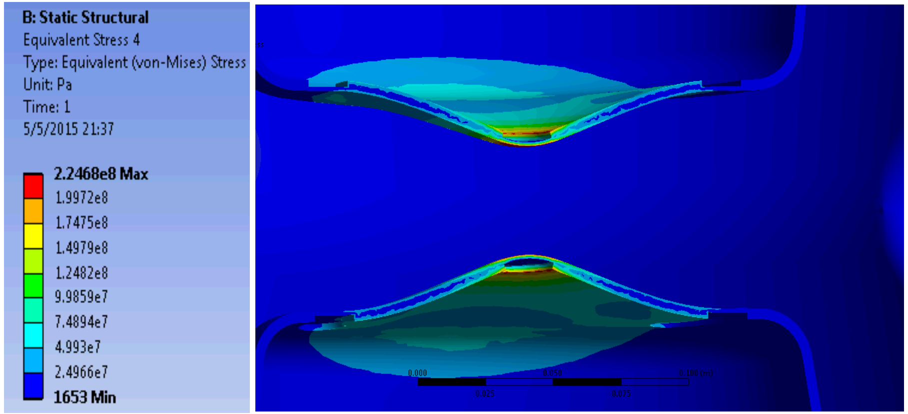
Cavity (RT , no PCB) with He vessel + pretuning device
Input force 2.5 kN

Displacement **z 0.53/0.6 mm**
Maximum eq. Stress **225 MPa**
Corresponds to about **0.21 MHz (0.42 MHz pp)** *

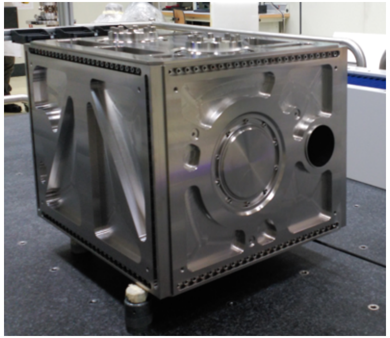
For 400 MPa/1.2= 333 MPa -> 0.31 MHz (0.62 MHz) range (linear), 3.7 kN, ±1.6 mm

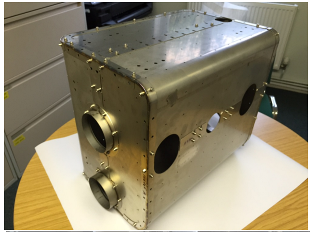
Force/tuner stroke **2.2 kN/mm**
199 MPa/mm

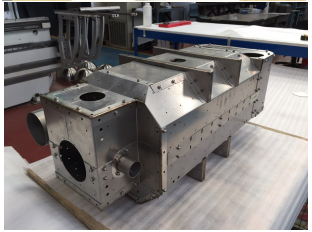
At RT for 50 MPa , 0.25 mm maximum tuner stroke for 0.5 kN



Prototype He Vessel, Manufacturing R&D







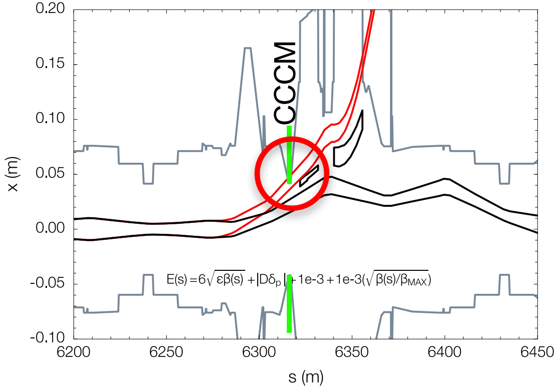
Internal magnetic shield
(UK contribution)

Successful pressure, vacuum & magnetic tests done

Compatibility of CCCM with SPS Operation

CCCM aperture

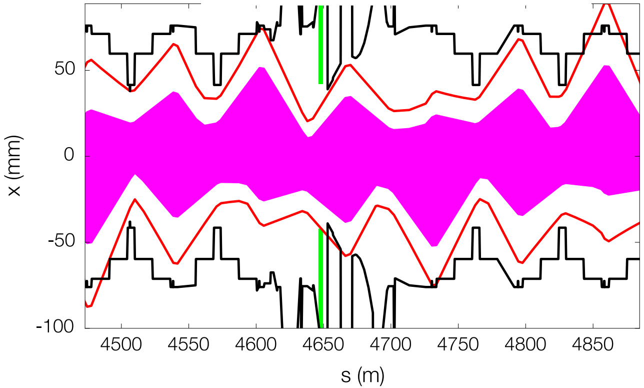
LHC beam extraction in LSS6



Fast extraction to LHC
Not enough aperture for extracted beam at nominal location close to QDA.617

H.Bartosik @
SPS Test Day, I
https://indico.cern.ch/event/463435/

CCCM after QDA.617



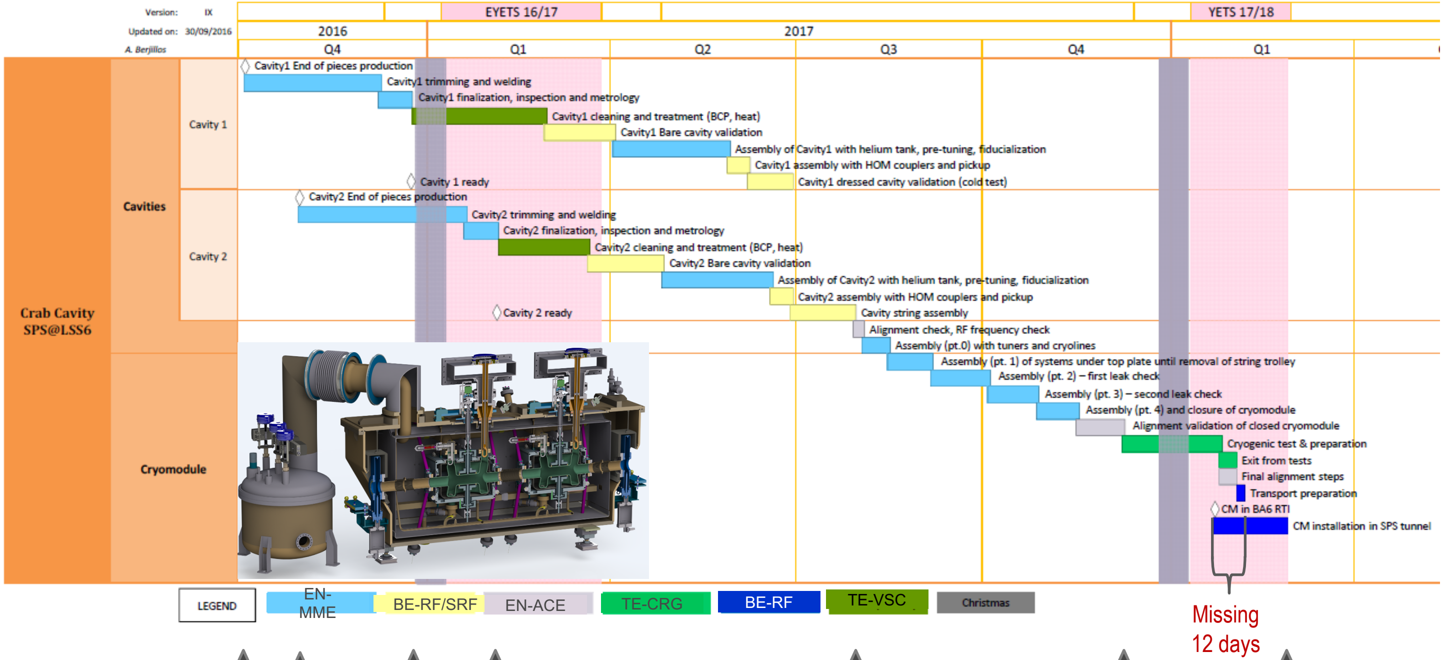
Slow extraction of fixed target beam at 400GeV, incl. extraction bump

purple : raw beam envelope
red: beam envelope + tolerance

Crab cavity at QD617 is compatible with slow extraction to North Area

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

SPS Tests Program – Weekly Schedule



Cavity #1 pieces produced 03/10/16

Cavity #2 pieces produced 28/10/16

Cavity #1 ready 22/12/16

Cavity #2 ready 02/02/17

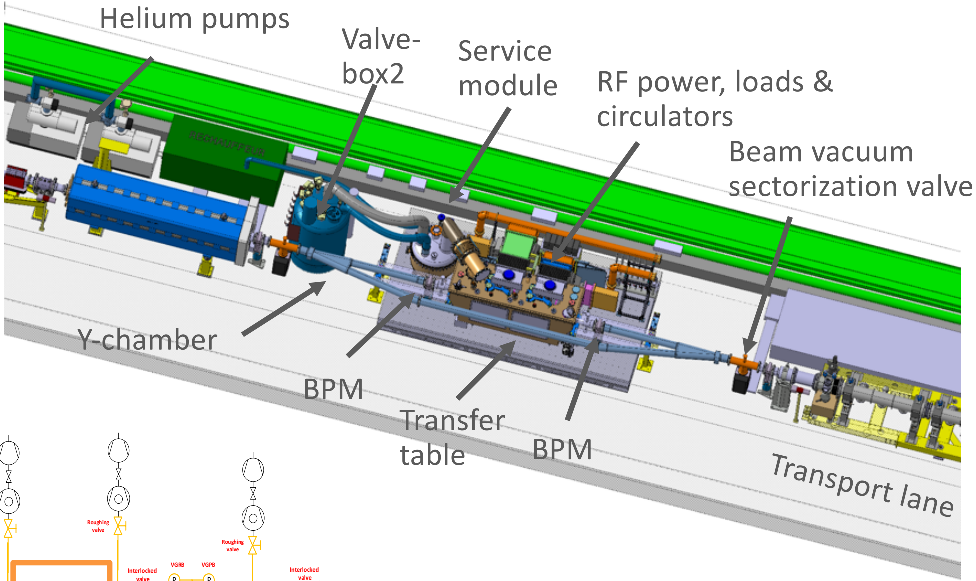
String assembled 27/07/17

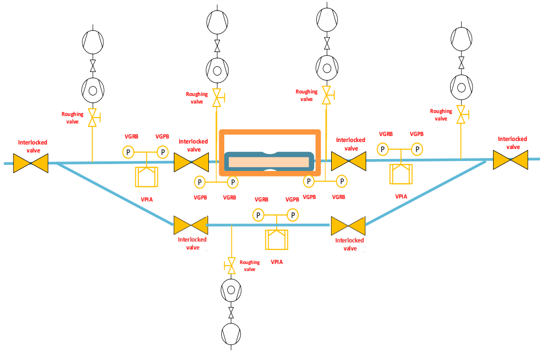
CM assembled 06/12/17

CM commissioned In SPS 23/02/18

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

Crab Cavity SPS Layout, LSS6



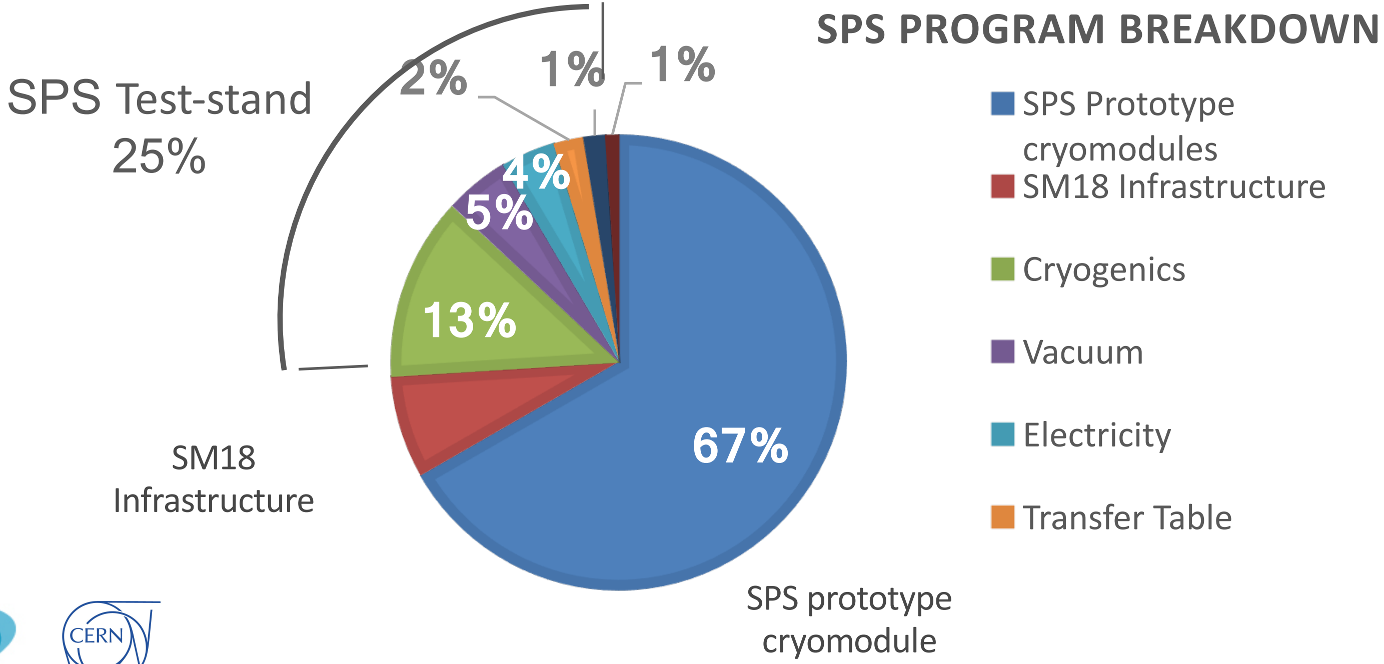


- 11^0 Y-chamber with multiple vacuum sectorization
- Movable table – 510 mm transversely (RF, Cryo, Vacuum)
- Approval from impedance working group to proceed with Y-chamber

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

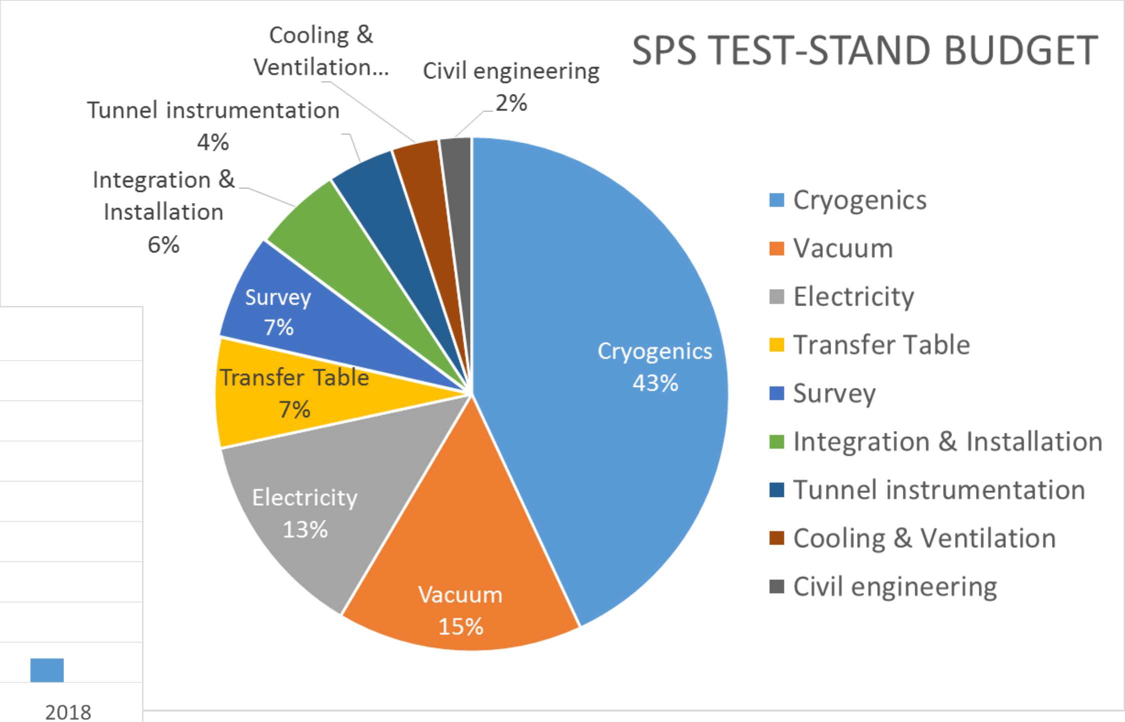
SPS test programme Budget

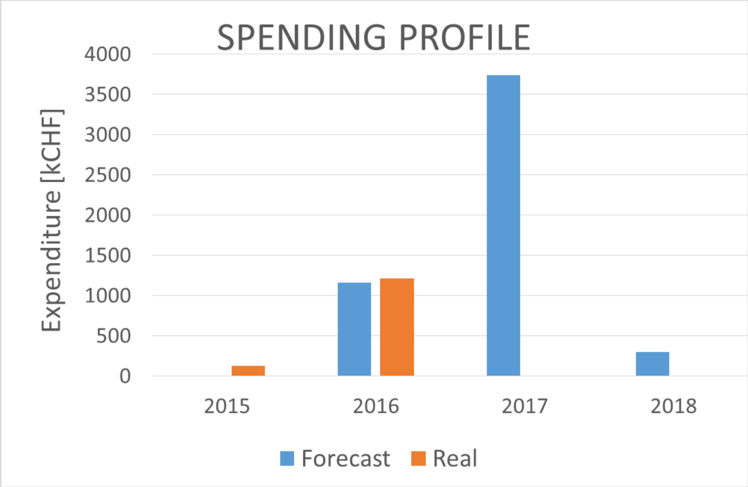
- WP4 Crab programme: 86.2 MCHF
  - SPS tests programme: 17.8 MCHF



*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016

SPS test-stand Budget





Overshoot of 4% of 2016 budget,
1% of total budget

*from G. Vandoni 2nd CERN-SRF Workshop Nov 2016