Summary of Session 5:
Impedance challenges for new projects

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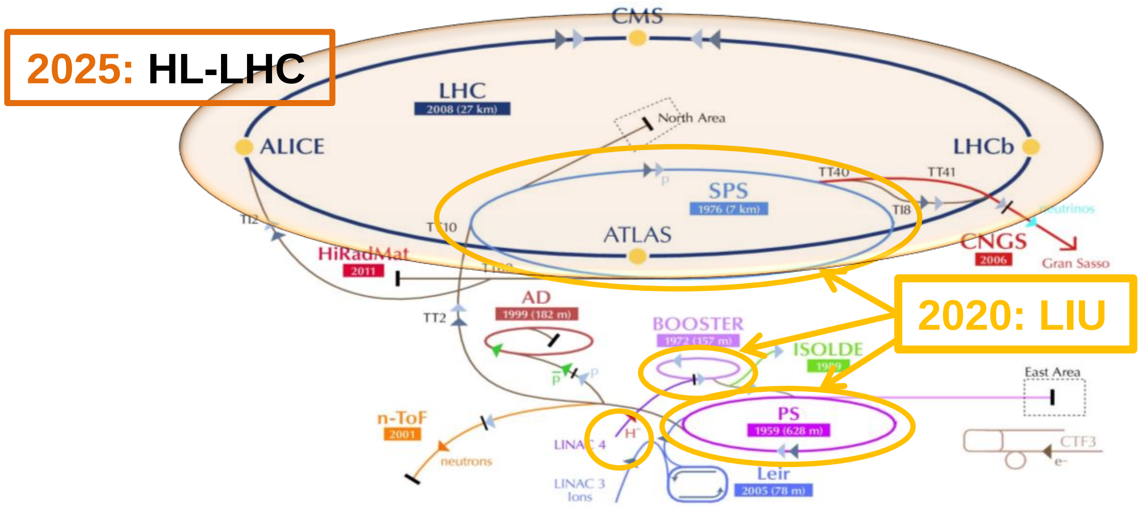
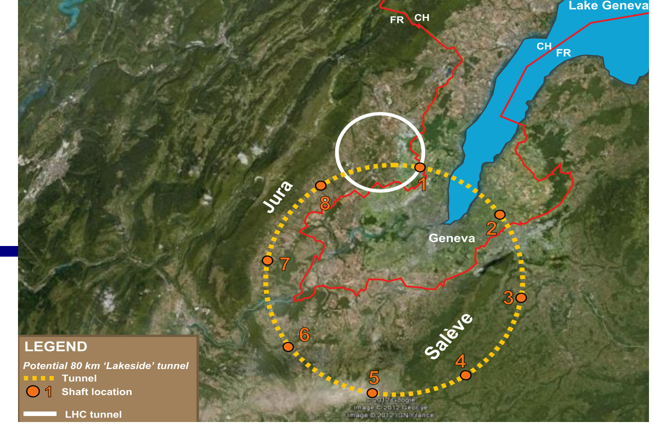
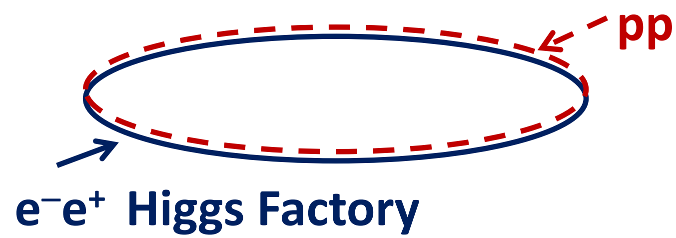
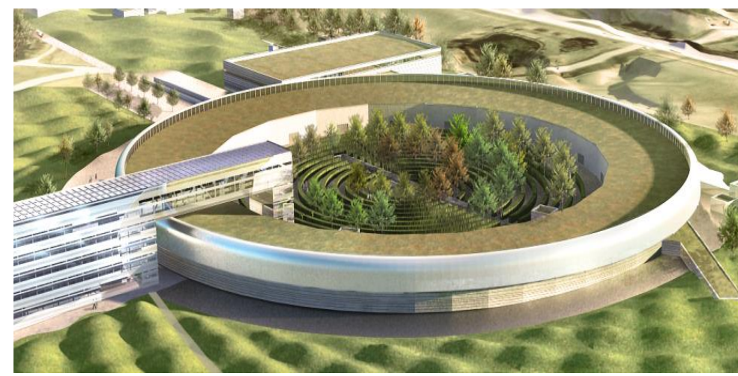
- **Four talks given in this session:**
  - **Challenges for the CERN projects (E. Shaposhnikova)**
  - **Challenges for the FAIR project at GSI (O. Boine-Frankenheim)**
  - **Challenges of Synchrotron Light Sources against Collective Effects (R. Nagaoka)**
  - **Challenges for the European XFEL Project at DESY (I. Zagorodnov)**

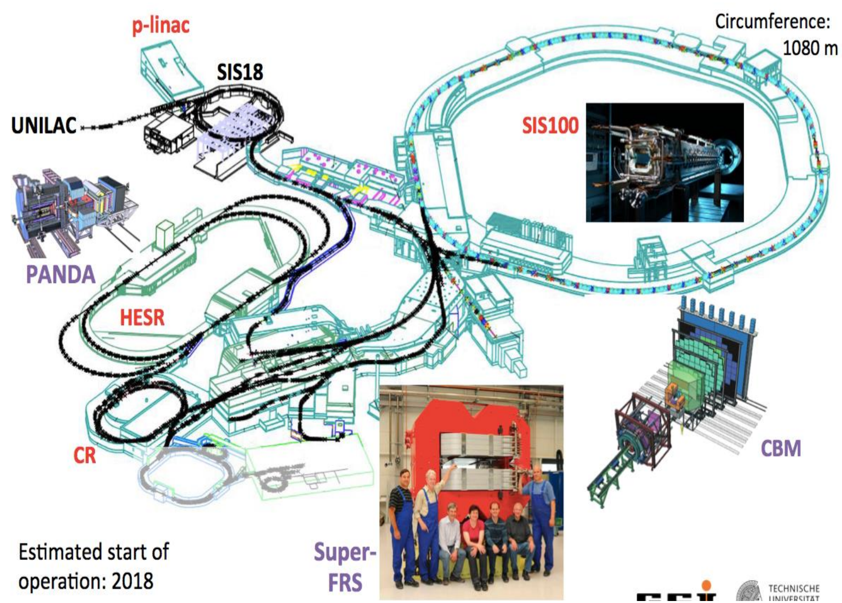
New Projects:

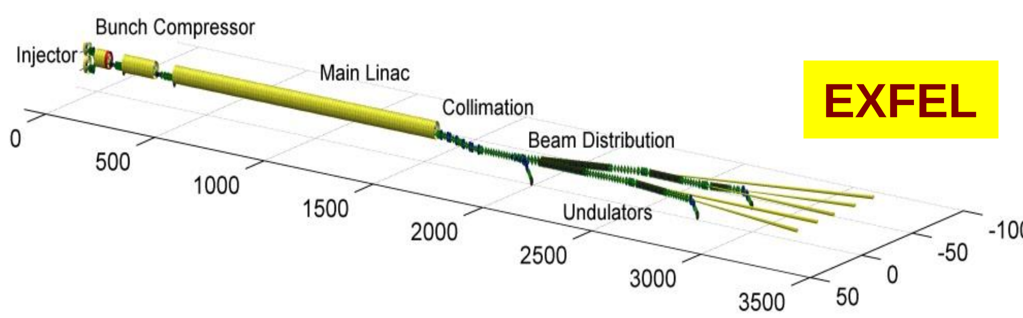












New Projects

- Upgrade from existing machines:
  - LIU, HL-LHC, ESRF, Super KEKB, …
- Partially upgraded from existing machine, but add new facility:
  - FCC, FAIR, …
- To be or being built:
  - CEPC, EXFEL, MAX-IV, Sirius, …

Requirements from new projects

High Beam Energy

High Luminosity, low background

High brightness, low beam loss

High beam power, low beam loss

Low impedance

Few collective effect

High reliability

Low heating load

Reduce impedance, cure instability

High energy

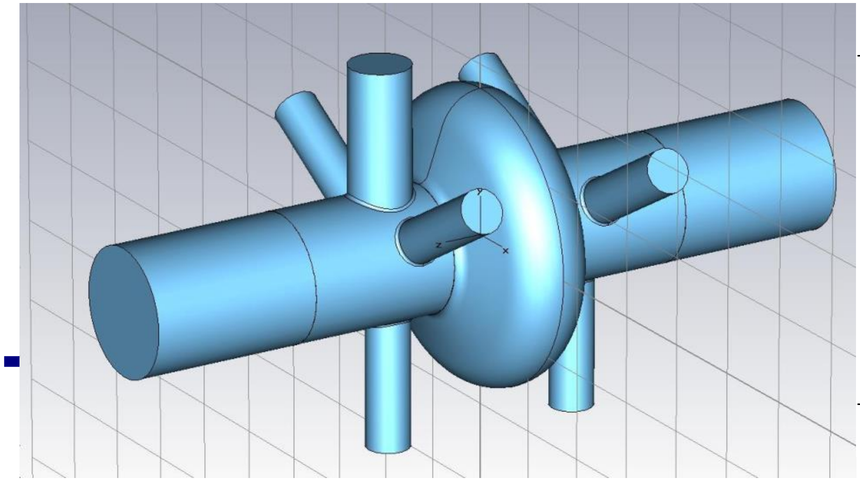
	units	LHC 2012	LHC 2015	HL-LHC 2025	FCC-hh
Beam energy	TeV	4.0	7.0	7.0	50.0
Luminosity (peak) levelled	$10^{34}cm^{-2}s^{-1}$	0.77	1	5	5
Bunch spacing	ns	**50**	**25**	25	25 (5)
Pile-up (peak/levelling)		21	28	**210/135**	170 (34)
Number of bunches n_b		1374	2808	2808	10600 (x5)
Bunch intensity N_b	10^{11}	1.7	1.15	**2.2**	1.0 (0.2)
Bunch length 4 σ_t σ_z	ns cm	1.25 9.4	1.05 7.875	1.0 7.5	1.07 8.0
Norm. transverse emit.	µm	1.7	2.6	2.1	2.2 (0.44)
Total beam intensity beam current I_{tot}	10^{14} A	2.3 0.45	3.2 0.58	**6.2** 1.1	10.6 0.5

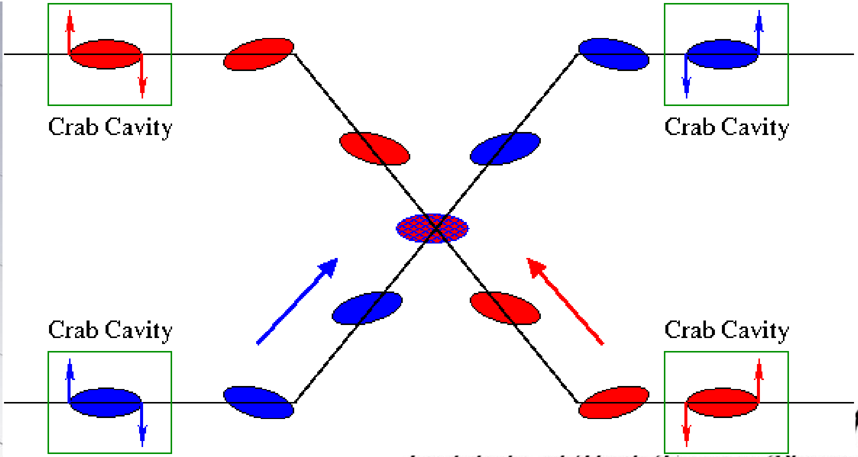
- Reliability of injectors – LIU (PSB, PS, SPS)
  - Increase beam brightness by push up space charge limit
  - Increase beam intensity by
    - new feedbacks – cure transverse instability in PSB, head tail instability in PS, CB instability in PS
    - measures against e-cloud – a-C coating, scrubbing & WB FB
    - reducing machine impedance – vacuum flange, damping resistors, travelling wave cavity, BPM, kicker, etc.
  - Impedance source & model – measurement & calculation

- FCC-hh
  - Transverse instability – cure with transverse FB
  - Beam screen – lower the SEY for e- and ion cloud
  - Synchrotron radiation at high magnetic fields
  - Choice of RF system and longitudinal impedance
- FCC-ee (and CEPC)
  - SR power
  - RF system (high voltage, beam loading, HOM damping, impedance of RF with high beam current, etc)
  - CSR, ECI, TMCI, CBI,…

High Luminosity

- **HL–LHC**
  - **Beam induced heating**
    - **Find and change the impedance source with modified ones, such as collimators, kickers, new detector chambers, etc.**
  - **Beam loading**
    - **Full cavity detuning, harmonic & crab cavity**





- **High luminosity for other e+e- machines**
  - **CEPC, like FCC-ee**
  - **Super KEKB – high beam current, modified vacuum chamber to lower ECI, etc.**
  - **Super T-c factory**

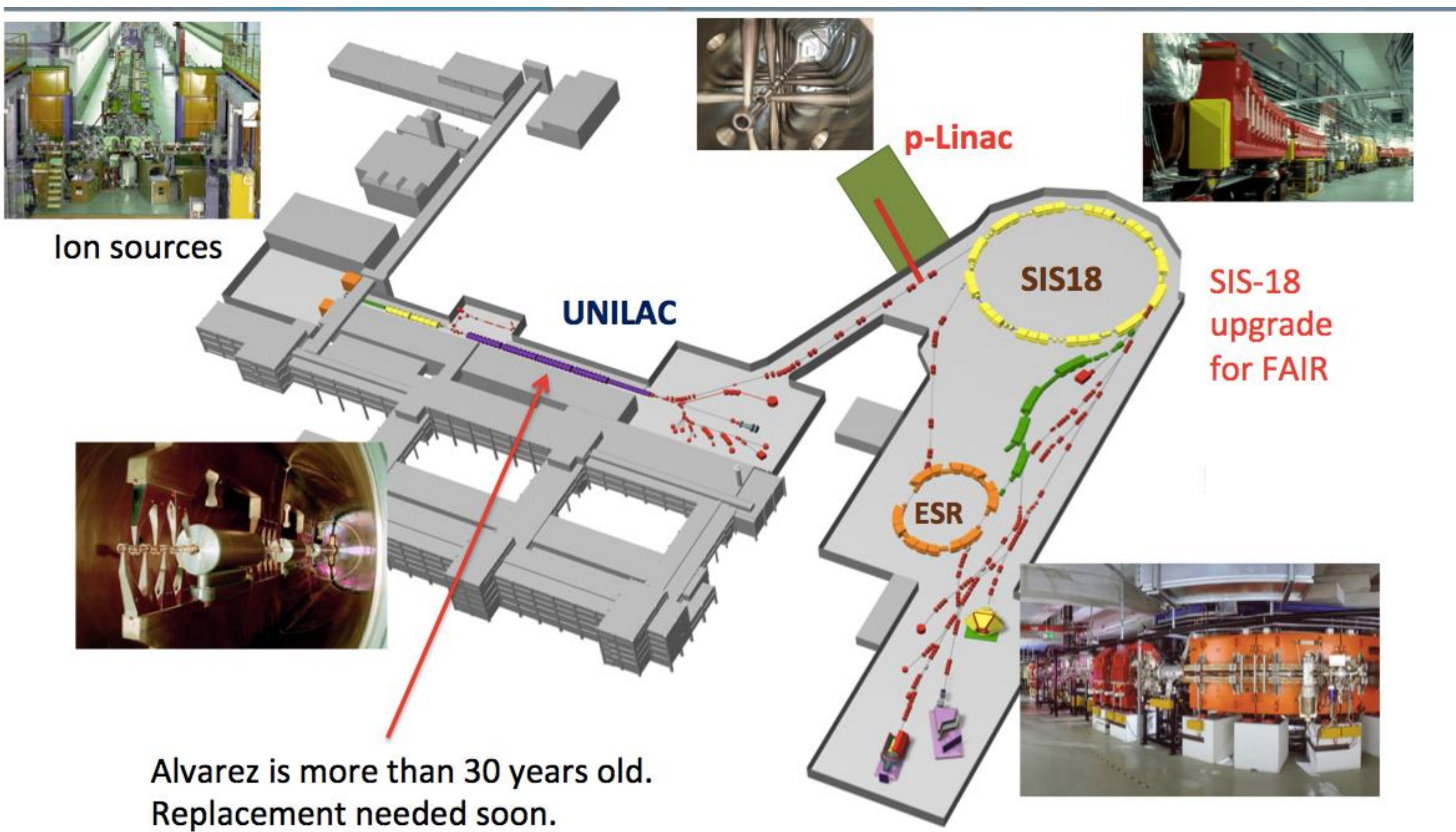
High beam power (high intensity)

- **FAIR – heavy ion chain, based on the existing UNILAC/SIS-18 at GSI**
- **Challenges:**
  - **Control of beam loading effects**
  - **Transverse space charge**

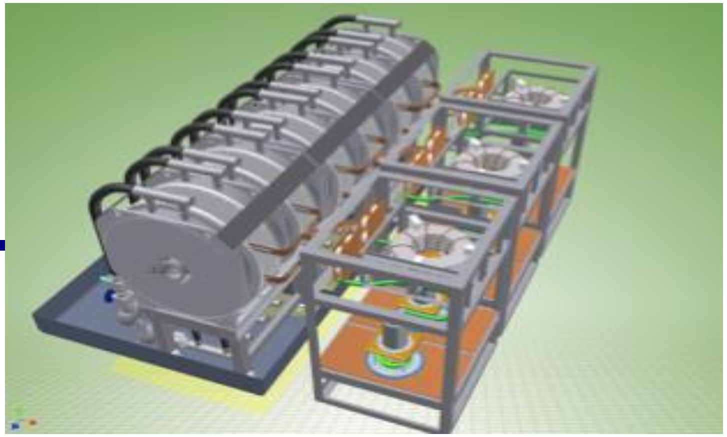
    $\Delta Q_y \approx -0.8$

	SIS-18	SIS-100
Reference primary ion	**U^{28+}** / U^{73+}	**U^{28+}** / U^{92+}
Reference energy	**0.2** / 1 GeV/u	**1.5** / 10 GeV/u
Ions per cycle	**1.2E11** / 2E10	**4E11** / 1E10
cycle rate (Hz)	2.7	**0.5** / 0.1
FAIR parameter booklet, **April 2007**, (Ed.) O. Boine-F., P. Spiller, M. Steck + corrections for MSV		

- **Upgrades from UNILAC & SIS-18**
  - **Replace the 30-year old Alvarez and upgrade SIS-18**

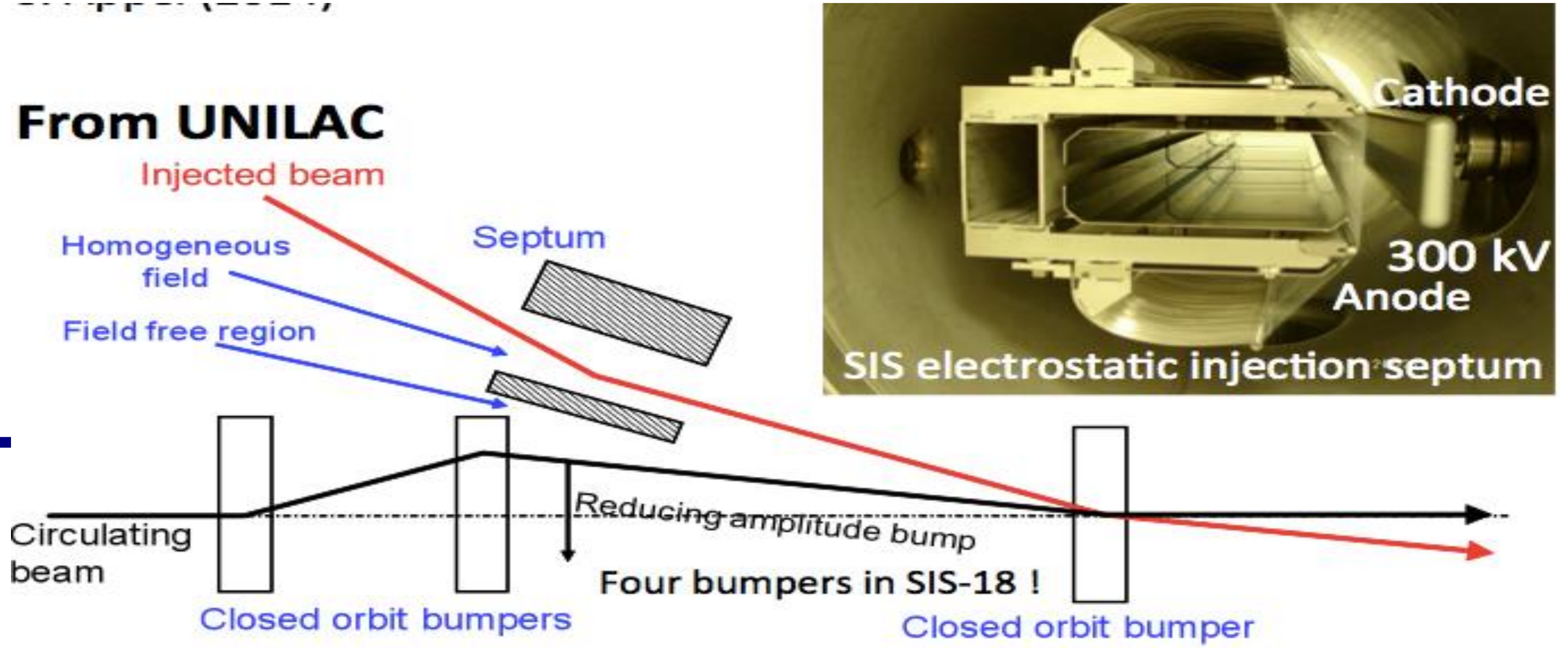


- **SIS-18 upgrade:**
  - New injection system
  - NEG coating
  - Reduction of multi-turn injection loss
  - Fast ramping with 10T/s
  - Dual (h=2/4) RF system



	SIS-18 today	FAIR design
Reference primary ion	U^{28+}	U^{28+}
Reference energy	200 MeV/u	200 MeV/u
Ions per cycle	**2E10**	**1.5E11**
cycle rate (Hz)	1 Hz	2.7 Hz

- **Upgrades of SIS-18**
  - Understanding the beam loss mechanics
  - Improving the vacuum condition
  - Coating vacuum chambers with NEG
  - New combined pumping/collimation ports
  - Reducing beam loss during stripping in injection
  - Control initial beam loss during multi-turn injection



- Challenges of FAIR rings
  - Space charge: protons vs heavy ions
    - Lifetime of intermediate charge state heavy-ion
    - Production of intermediate charge state ions
    - IBS induced diffusion
  - Collective effects
    - Incoherent space charge
    - Impedance – image current, resistive
    - coherent instabilities
  - Secondary particles – ECI
  - IBS

- Other challenges in SIS-100 ring
  - Magnet field quality
  - Thin S.S. beam pipe
  - Heat load due to longitudinal impedance

High brightness

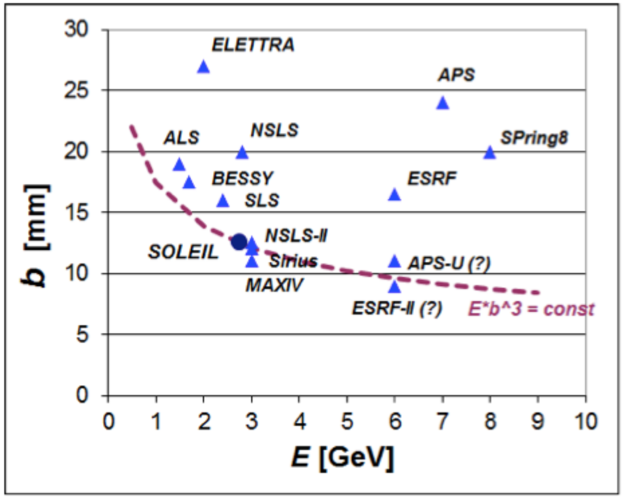
$$Brilliance = \frac{Photons}{Second \cdot mrad^2 \cdot mm^2 \cdot 0.1\%BW}$$

Two principal ways of increasing the brilliance:

- Lowering the beam tranverse emittance
- Increasing the beam intensity

However, they result in enhancing the problems of collective effects due to the following (entangled) reasons:

- $I_{operation} > I_{threshold}$
- Low emittance → stronger focusing → smaller bore radii → smaller chamber aperture → larger impedance

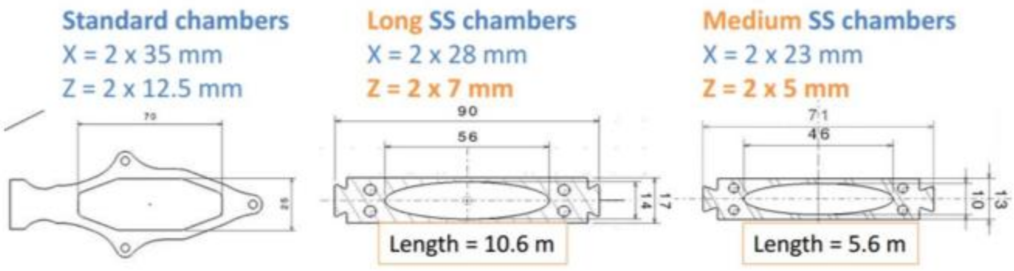


Vertical half aperture versus energy for

Ultra low emit. makes rings more sensitive to collective effects
Impedance control/minimization becomes of high importance

- **Special challenges comes from very small gap IDs**
  - **Induce many transitions/tapers and low gap chambers**
  - **Source of impedance**

Low gap chamber in a 12 m long straight section in SOLEIL

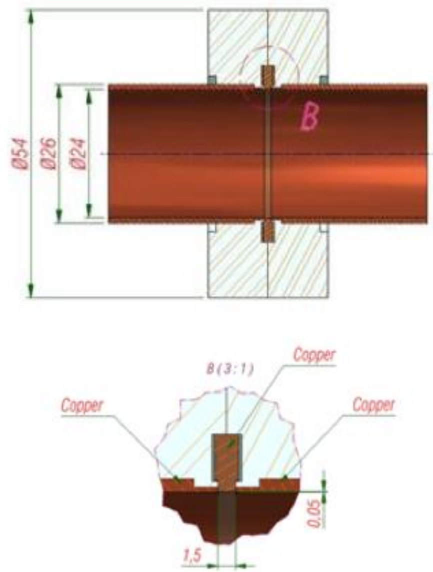


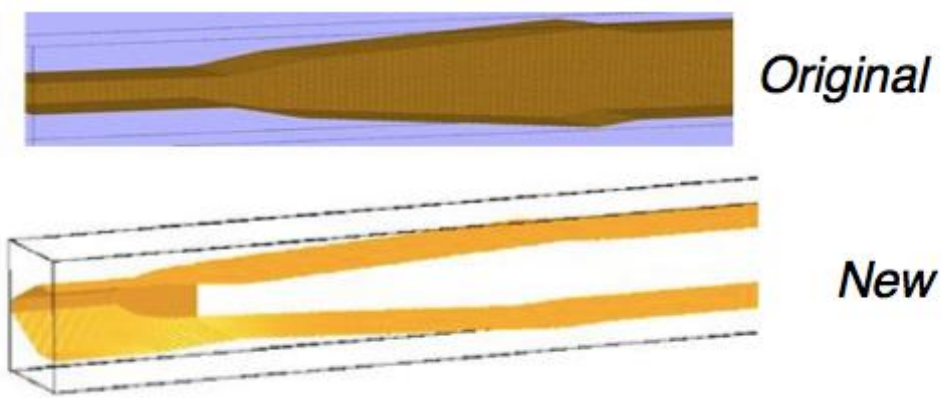
Three type of vacuum chambers in SOLEIL, P. Brunelle, TWIICE 2014)

Survey of ultra-low-emit lattices

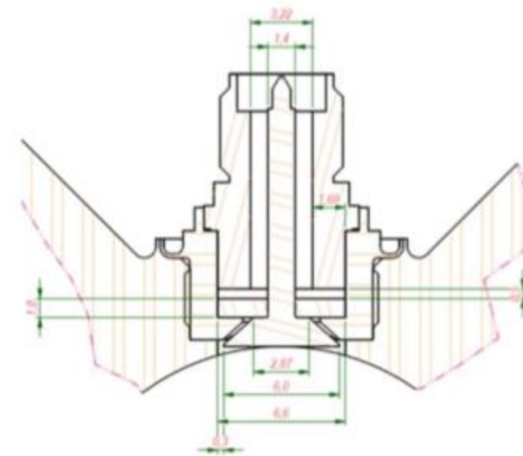
MAX IV	7BA	3 GeV	320 pm	500 mA	SS length 5m	DA 7mm w/errors
Sirius	5BA w/superbend	3	280	500	5m & 6m	5 mm w/errors
Spring-8	6BA	6	67.5	300	4.5m & 27m	3 mm w/errors
APS	7BA	6	147	100		
Pep-X	7BA	4.5	11	200	5 m	10 mm w/errors
ESRF Phase II	7BA	6	130	200	5m	10 mm
SOLEIL	QBA w/longit.. gradient dipole	2.75	980 (220)	500		Robins. Wiggler + beam adapter
Diamond	mod. 4BA, 5BA, 7BA	3	45-300	300	5m & 7 m	2 mm
ALS	5BA - 7BA	2	50-100	500	5 m	2-3 mm
BAPS	7BA-15BA	5	50	150	10m & 7m	10 mm w/errors
tUSR	7BA	9	3	100	TEV tunnel	0.8 mm

- **Identify impedance sources and improve**
  - **Flange: zero impedance flange (KEK, Sirius)**
  - **BPM: optimize button shape, etc.**
  - **Taper: nonlinear taper geometry, minimize the length of tapers**





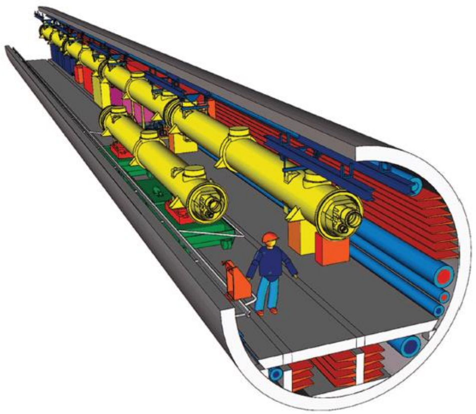
Variable in-vacuum ID tapers at SOLEIL

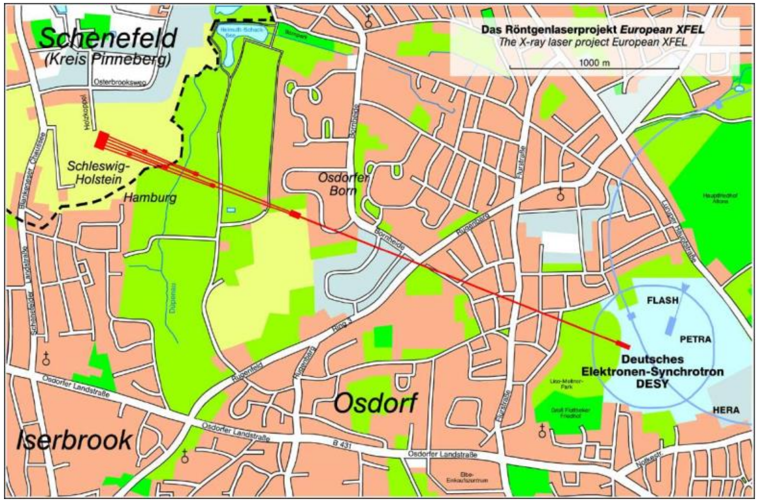


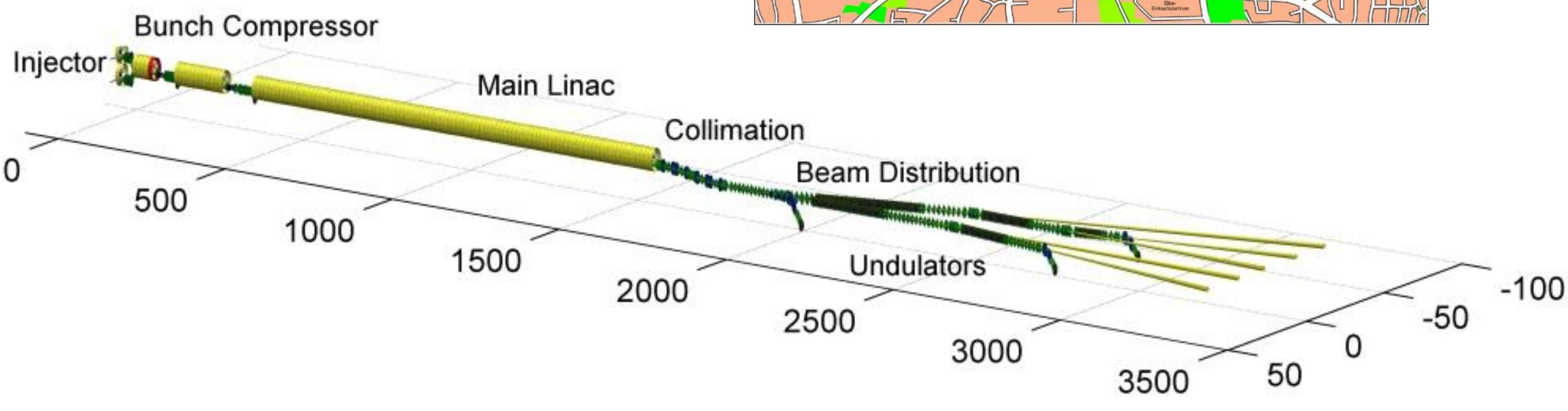
– **NEG coating:**
  - indispensable technology in future USRs
  - observations showed some concerns on impedance
  - Need more studies on NEG coating impedance
– **Ceramic chamber coating and heating problem**
  - Used for pulsed magnets
  - Important to optimize Ti coating
  - Peak power density enhanced for low-gap flat chambers
  - Analytical studies are necessary
  - Will be important for USRs

- Cure of collective effects
  - Minimize impedance
  - Simulation studies (construct impedance model, develop macro-particle tracking code)
  - Study collective effects in LSRs (TMCI, HT, ion-trapping, FBII, etc)
  - FB system

Linac-based light source – FEL (EXFEL, SACLA, LCLS)







	Linac Coherent Light Source (LCLS)	Spring-8 Angstrom Compact Laser (SACLA)	European XFEL
Location	USA	Japan	Deutschland
Start of commissioning	2009	2011	2016
Accelerator technology	normal conducting	normal conducting	**superconducting**
Number of light flashes per second	120	60	**27 000**
Minimum wavelength	0.15 nm	0.1 nm	**0.05 nm**
Length of the facility	3000 m	750 m	3400 m

- **Challenges from FELs**
  - **Chamber Wakefields in Bunch Compressors**
  - **Impact of All (Longitudinal+Transverse) Wakes on the results of Start-to-End Simulations**
  - **Transverse Impedance Database**
  - **Impact of Transverse Wakes on FEL Performance**

• Wakes calculations for elements of EXFEL

– Cavity and coupler
  - TESLA cryomodule
  - Coupler kick
  - Transverse deflecting structure
  - 3rd harmonic section
– Tapered collimators
– Short/long 3D-step and round collimators
– High-frequency impedance
  - Optical approximation
  - Laser mirror of RF gun
  - OTR screens
  - etc

– **Resistive, roughness, oxide layer**
  - **Round resistive pipe**
  - **Round vs elliptical pipe**

– **Undulator**

N	Element	from	to	Effective Length	Material	Conduct.	Relax. Time	Oxid layer	Rough ness
		mm	mm	mm		1/Omm/m	sec	nm	nm
1	Eliptical pipe	0	5288	5161	Aluminium	3,66E+07	7,10E-15	5	300
2	Pump	5161	5266	105	Aluminium	3,66E+08	7,10E-15	5	300
3	Absorber/Round transition	5266	5288	22	Copper	5,80E+07	2,46E-14	5	300
4	Round pipe	5288	6100	652	Copper	5,80E+07	2,46E-14	5	300
5	Below	5288	5318	30	BeCu 174	2,78E+07	2,46E-14	5	300
6	BPM	5373	5473	100	Stainless Steel 304	1,40E+06	2,40E-15	5	300
7	Below	5513	5543	30	BeCu 174	2,78E+07	2,46E-14	5	300
8	Round/Eliptical transition	6100	6100	0					

Impedance model and database

$$w(s) = \underbrace{w^{(0)}(s) + \frac{1}{C}}_{\text{regular part}} + \underbrace{Rc\delta(s) - c\frac{\partial}{\partial s}\left[Lc\delta(s) + w^{(-1)}(s)\right]}_{\text{singular part (cannot be tabulated directly)}}$$

regular part

singular part
(cannot be tabulated directly)

$$Z(\omega) = Z^{(0)}(\omega) - \frac{1}{i\omega C} + R + i\omega\left[L + Z^{(-1)}(\omega)\right]$$

capacitive: $W \sim \int \lambda(s)ds$

resistive: $W \sim \lambda(s)$

inductive: $W \sim \lambda'(s)$

$$\frac{\partial}{\partial s} w^{(-1)}(s) = o(s^{-1}), \qquad s \to 0,$$

it describes singularities $s^{-\alpha}$, $\alpha<1$

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- **Database**

Wake Field Calculations for the XFEL Project

Search:

Type of element:			R (Omm):	L (H):	C_inv (1/F) :	Link to w0	Link to w_1
ABS	Absorber/Round transition	☑	2.04E+01	0.00E+00	0.00E+00	AbsRes22mm.dat	0
BEL	Bellow	☑	7.60E-01	0.00E+00	0.00E+00	BellowRes30mm.dat	BellowDiff1.dat
BPM	BPM	☑	0.00E+00	0.00E+00	0.00E+00	BPMRes100mm.dat	BPMdiff1.dat
PIPE	Elliptical pipe	☑	0.00E+00	0.00E+00	0.00E+00	ElPipe5161mm.dat	0
PIPR	Round pipe	☑	0.00E+00	0.00E+00	0.00E+00	RoundPipe652mm.dat	0
PUM	Pump	☑	1.13E+00	1.66E-13	0.00E+00	PumpRes105mm.dat	0
RET	Round/Elliptical transition	☑	1.06E+01	0.00E+00	0.00E+00	0	0
*		☑	0.00E+00	0.00E+00	0.00E+00		

General data | Wake

Record: 2 of 7

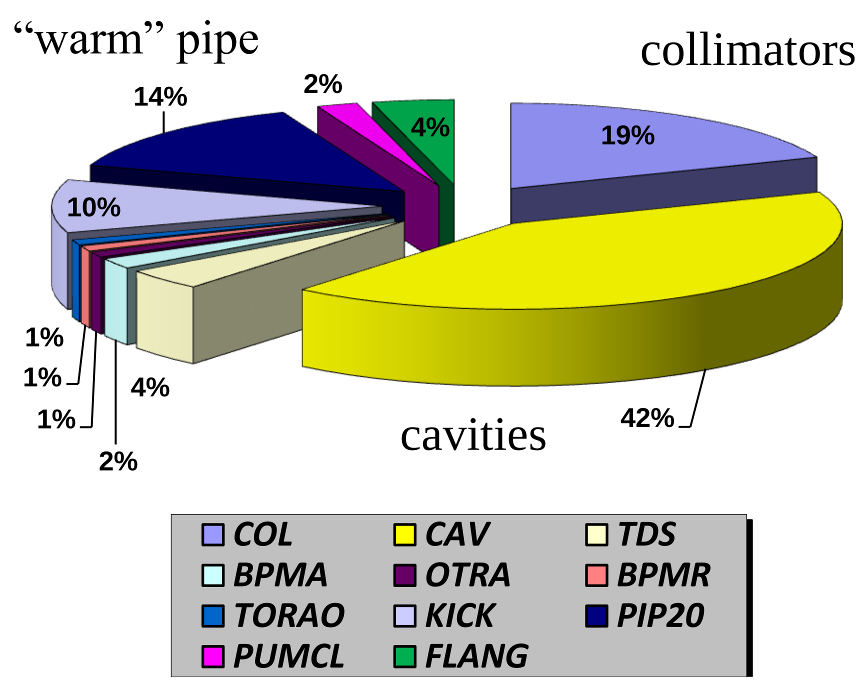
Loss, spread, peak parameters

Section	Type of element	Number	Loss (V/pC)	%	Spread (V/pC/m)	%	Peak (V/pC/m)	%
SA1	ABS	32	2.389E+03	14	8.717E+02	7	3.451E+03	12
SA1	BEL	64	1.342E+03	8	4.476E+02	3	1.803E+03	6
SA1	BPME	33	1.780E+03	11	7.243E+02	6	2.598E+03	9
SA1	PIPE	33	8.730E+03	53	1.020E+04	80	1.844E+04	62
SA1	PIPR	32	7.812E+02	5	1.157E+03	9	2.069E+03	7
SA1	PUM	32	3.025E+02	2	2.383E+02	2	5.476E+02	2
SA1	RET	32	1.228E+03	7	4.422E+02	3	1.766E+03	6
SA1			1.655E+04	100	1.283E+04	100	2.951E+04	100
			1.655E+04	100	1.283E+04	100	2.951E+04	100

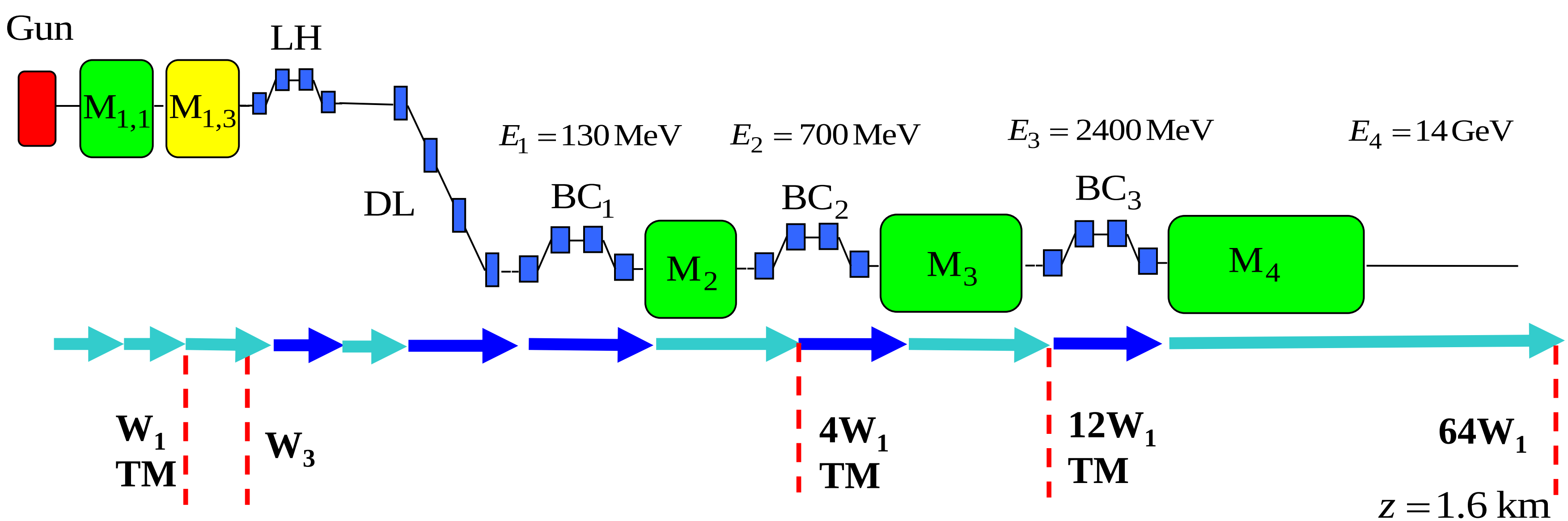
Accelerator wakes. Q=1nC

Impedance Budget (list of elements)

El.type	Num.	Loss (kV/nC)	%	Spread (kV/nC)	%	Peak (kV/nC)	%
BPMF	4	4.075E+01	0	1.858E+01	0	5.804E+01	0
COL	7	6.725E+03	19	3.373E+03	22	1.058E+04	21
KICK	3	3.645E+03	10	1.459E+03	9	5.283E+03	10
PIP20	1	5.116E+03	14	3.661E+03	24	8.959E+03	18
PUMCL	78	5.605E+02	2	2.363E+02	2	7.946E+02	2
CAV	808	1.481E+04	42	8.842E+03	57	2.814E+04	56
CAV3	8	8.084E+01	0	3.010E+01	0	1.117E+02	0
FLANG	500	1.330E+03	4	5.610E+02	4	1.886E+03	4
TDS	8	1.507E+03	4	7.348E+02	5	2.174E+03	4
OTRB	8	1.584E+02	0	7.251E+01	0	2.254E+02	0
STEP1	1	3.010E+00	0	5.969E-01	0	3.441E+00	0
BPMA	107	5.654E+02	2	2.896E+02	2	8.670E+02	2
OTRA	12	3.078E+02	1	1.274E+02	1	4.494E+02	1
BPMC	56	4.431E+01	0	2.138E+01	0	6.805E+01	0
BPMR	26	2.993E+02	1	1.304E+02	1	4.501E+02	1
DCM	4	1.644E+01	0	7.479E+00	0	2.315E+01	0
BPMB	27	5.744E-02	0	1.587E-01	0	6.023E-01	0
BAM	5	3.319E+00	0	1.494E+00	0	4.768E+00	0
TORA	3	3.147E+01	0	1.609E+01	0	4.763E+01	0
TORAO	6	1.856E+02	1	7.684E+01	0	2.700E+02	1
		3.530E+04	100	1.540E+04	100	5.037E+04	100



Start-to-end simulations with wakes



ASTRA (tracking with **3D space charge**, DESY, K. Flötmann)

CSRtrack (tracking through dipoles, DESY, M. Dohlus, T. Limberg)

W1 -TESLA cryomodule wake (TESLA Report 2003-19, DESY, 2003)

W3 - ACC39 wake (TESLA Report 2004-01, DESY, 2004)

TM - transverse matching to the design optics

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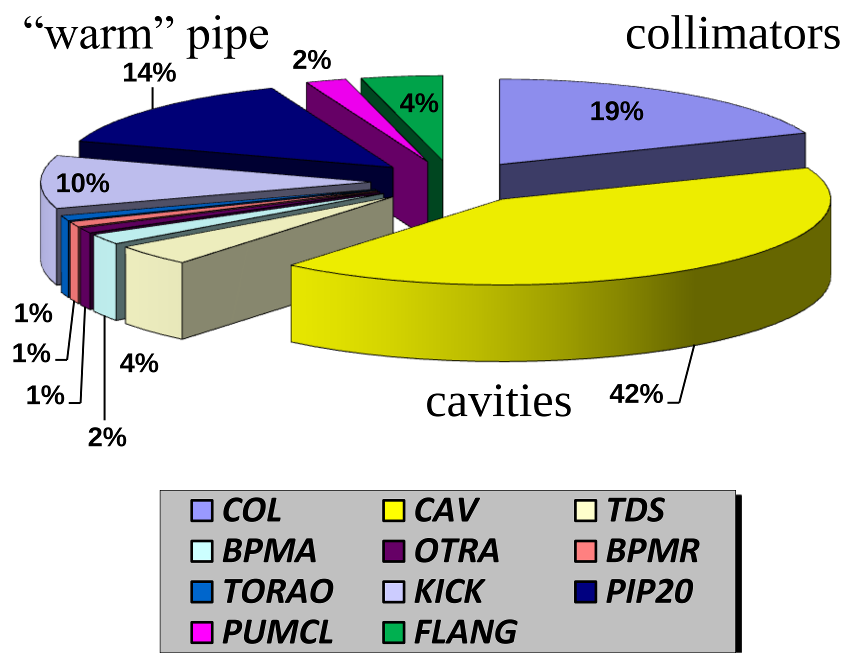
Impact of Accelerator Wakes on SASE

Impedance Budget (list of elements)

El.type	*Num.*	*Loss (kV/nC)*	*%*	*Spread (kV/nC)*	*%*	*Peak (kV/nC)*	*%*
BPMF	**4**	4.075E+01	0	1.858E+01	0	5.804E+01	0
COL	**7**	6.725E+03	19	3.373E+03	22	1.058E+04	21
KICK	**3**	3.645E+03	10	1.459E+03	9	5.283E+03	10
PIP20	**1**	5.116E+03	14	3.661E+03	24	8.959E+03	18
PUMCL	**78**	5.605E+02	2	2.363E+02	2	7.946E+02	2
CAV	**808**	1.481E+04	42	8.842E+03	57	2.814E+04	56
CAV3	**8**	8.084E+01	0	3.010E+01	0	1.117E+02	0
FLANG	**500**	1.330E+03	4	5.610E+02	4	1.886E+03	4
TDS	**8**	1.507E+03	4	7.348E+02	5	2.174E+03	4
OTRB	**8**	1.584E+02	0	7.251E+01	0	2.254E+02	0
STEP1	**1**	3.010E+00	0	5.969E-01	0	3.441E+00	0
BPMA	**107**	5.654E+02	2	2.896E+02	2	8.670E+02	2
OTRA	**12**	3.078E+02	1	1.274E+02	1	4.494E+02	1
BPMC	**56**	4.431E+01	0	2.138E+01	0	6.805E+01	0
BPMR	**26**	2.993E+02	1	1.304E+02	1	4.501E+02	1
DCM	**4**	1.644E+01	0	7.479E+00	0	2.315E+01	0
BPMB	**27**	5.744E-02	0	1.587E-01	0	6.023E-01	0
BAM	**5**	3.319E+00	0	1.494E+00	0	4.768E+00	0
TORA	**3**	3.147E+01	0	1.609E+01	0	4.763E+01	0
TORAO	**6**	1.856E+02	1	7.684E+01	0	2.700E+02	1
		3.530E+04	100	1.540E+04	100	5.037E+04	100

Accelerator wakes. Q=1nC



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	Accelerator wake	Bunch charge, nC		
		1	0.25	0.02
Energy in the radiation pulse at z=175 m, mJ	x1	9	2.3	0.46
	x4	8	2.3	0.44
	x8	6	2.3	0.43
Spectrum width at z=85m, %	x1	0.14	0.29	0.55
	x4	0.23	0.30	0.58
	x8	0.6	0.38	1.0

Conclusions

- Impedance issue is of importance for future project, high energy and high luminosity colliders, ring-based and linac-based light sources, hadron or heavy ion facilities.
- Be considered seriously in the existing machine for upgrades and new facilities to be built.
- Techniques for low impedance element is developed.
- Collective effects should be cured with some measures.
- Impedance model, analytical method, simulation, are being developed.