SRF2013
PARIS
16th International conference on RF Superconductivity
September 23-27, 2013
Cité Internationale Universitaire, PARIS

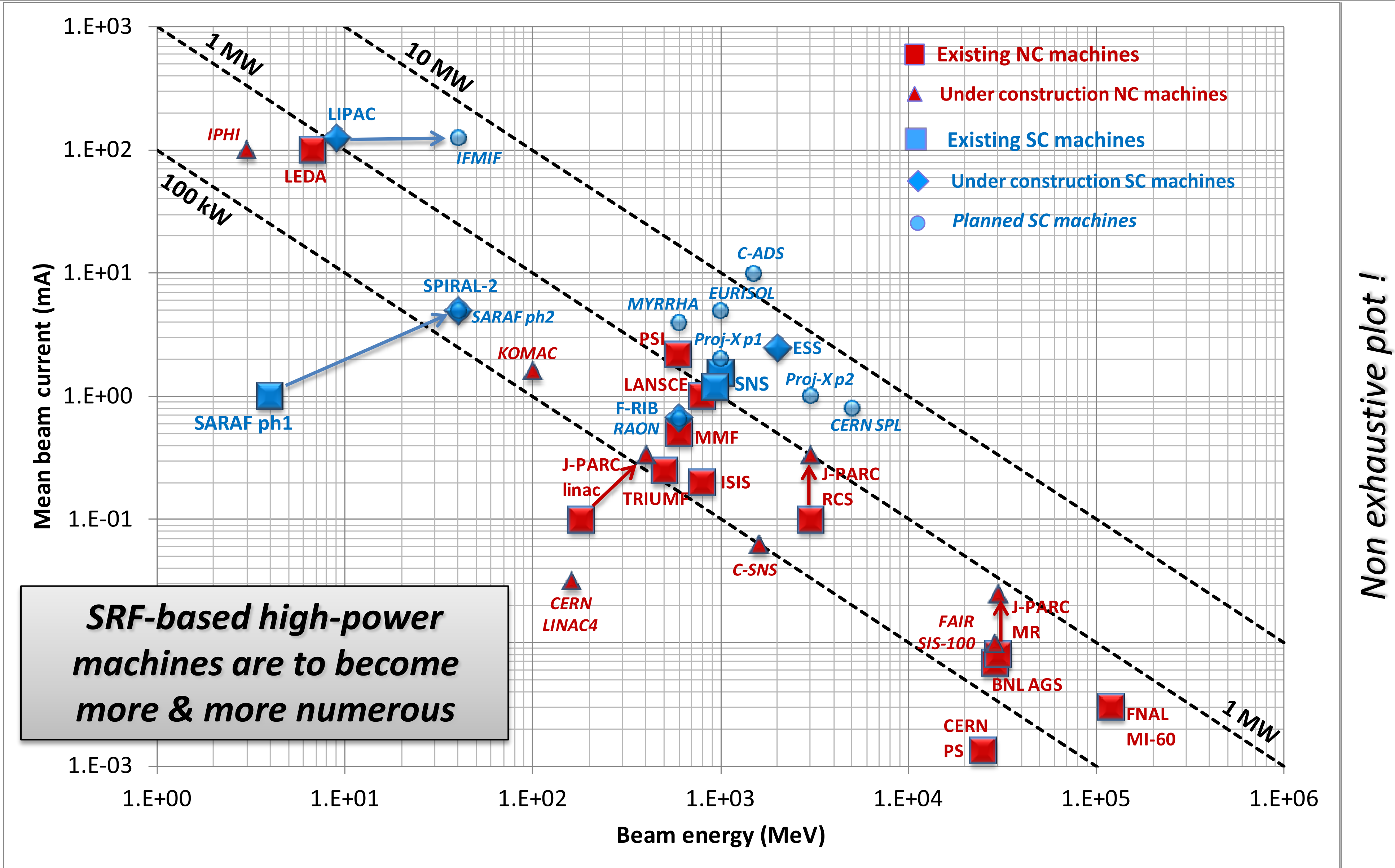
High power proton/deuteron accelerators

J-Luc Biarrotte *(CNRS, IPN Orsay)*

1. General overview

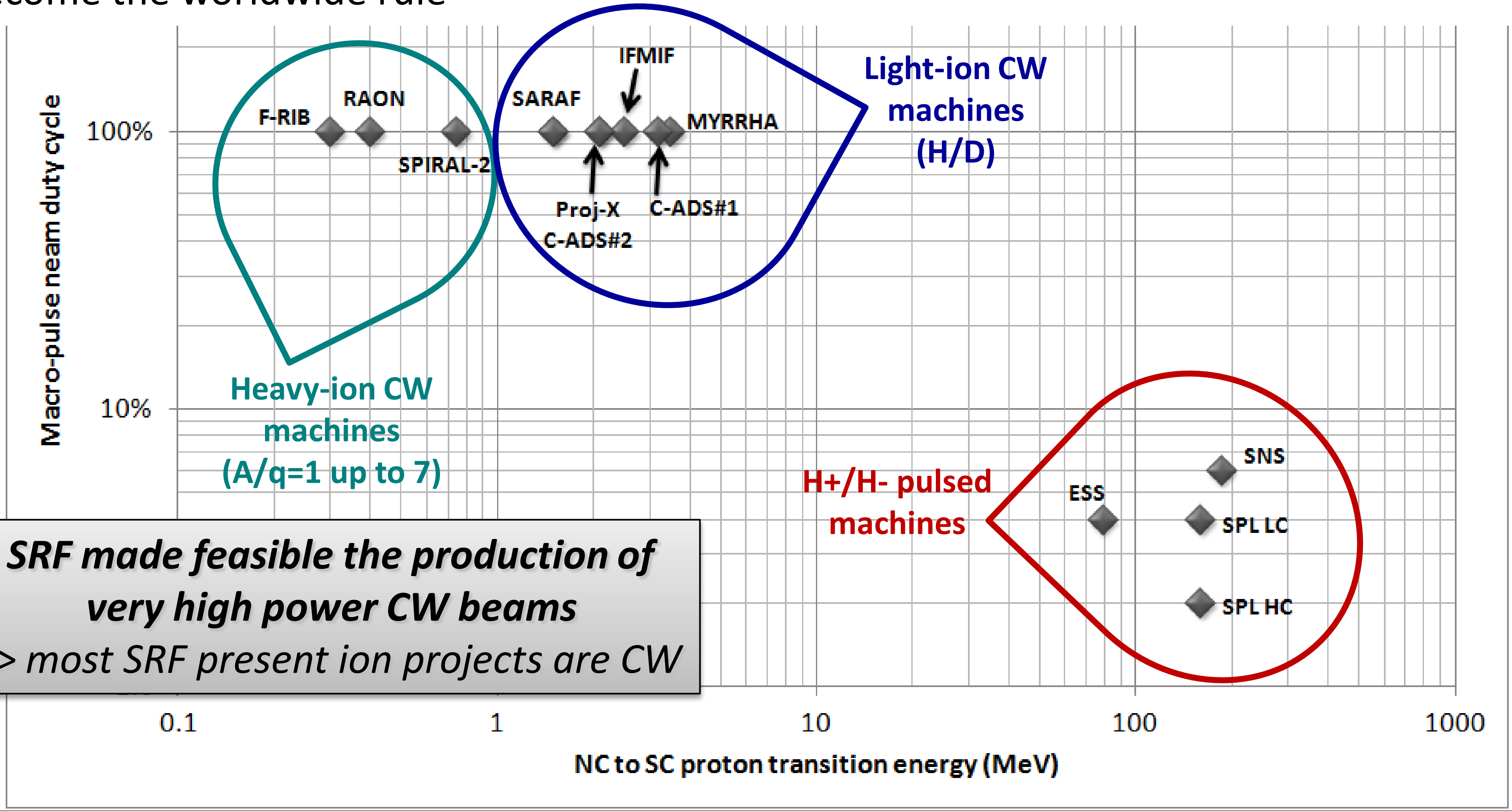
2. Elliptical-based SRF H linacs
3. Fully-SRF CW H/D linacs
4. Summary

High power H/D beams around the world



High power SRF linacs: NC to SC transition

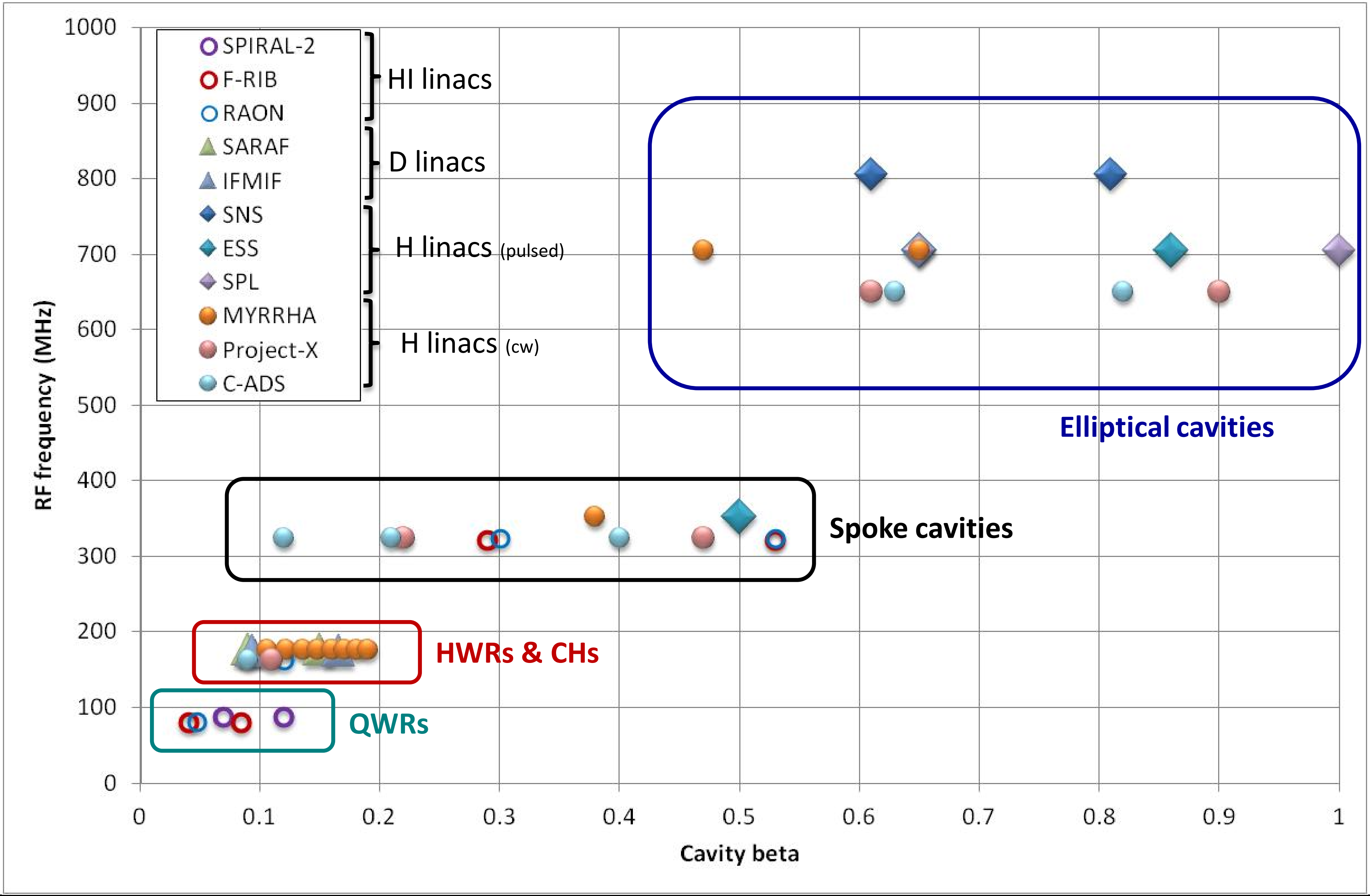
- **NC/SC transition** ideally minimizes overall power consumption ~ DC*(P_{cav}+P_{beam}) + P_{cryo}
- **For CW operation**, "SRF As Low As Reasonable Achievable" (i.e. down to the RFQ) has become the worldwide rule



SRF made feasible the production of very high power CW beams
-> most SRF present ion projects are CW

Non exhaustive plot !

High power SRF linacs: RF structures



Non exhaustive plot !

High power H/D SRF linacs

The ones I will NOT talk about

- **Heavy-ions high power linacs** Refer to R. Ferdinand MOIOA-02
  - ✓ SPIRAL-2, that will be the <u>world first CW high power SC linac </u>for p, d & A/q=3 ions
  - ✓ F-RIB Refer to M. Leitner MOIOA-01
  - ✓ RAON Refer to D. Jeaon MOIOA-05
- **Long-term planned SC upgrades of NC machines**
  - ✓ J-PARC -> 400 MeV ACS upgrade in construction, upgrades using SRF foreseen (R&D might restart in 2014)
  - ✓ C-SNS -> 80 MeV DTL in construction, upgrade using SRF spoke cavities foreseen
  - ✓ KOMAC -> 100 MeV DTL in construction, 1 GeV upgrade using SRF foreseen
- **“Far future” projects with low visibility and/or poor R&D activities** (Eurisol, Indian-ADS…)

High power H/D SRF linacs

The ones I will talk about

- **The present reference = SNS**
- **The "under construction" machines (or nearly)**
  - ✓ ESS
  - ✓ SARAF
  - ✓ LIPAC (IFMIF demonstrator)
  - ✓ PXIE (Project X demonstrator)
- **The other "under design" on-going projects (the major ones)**
  - ✓ SPL
  - ✓ MYRRHA
  - ✓ C-ADS

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The SNS @ Oak Ridge

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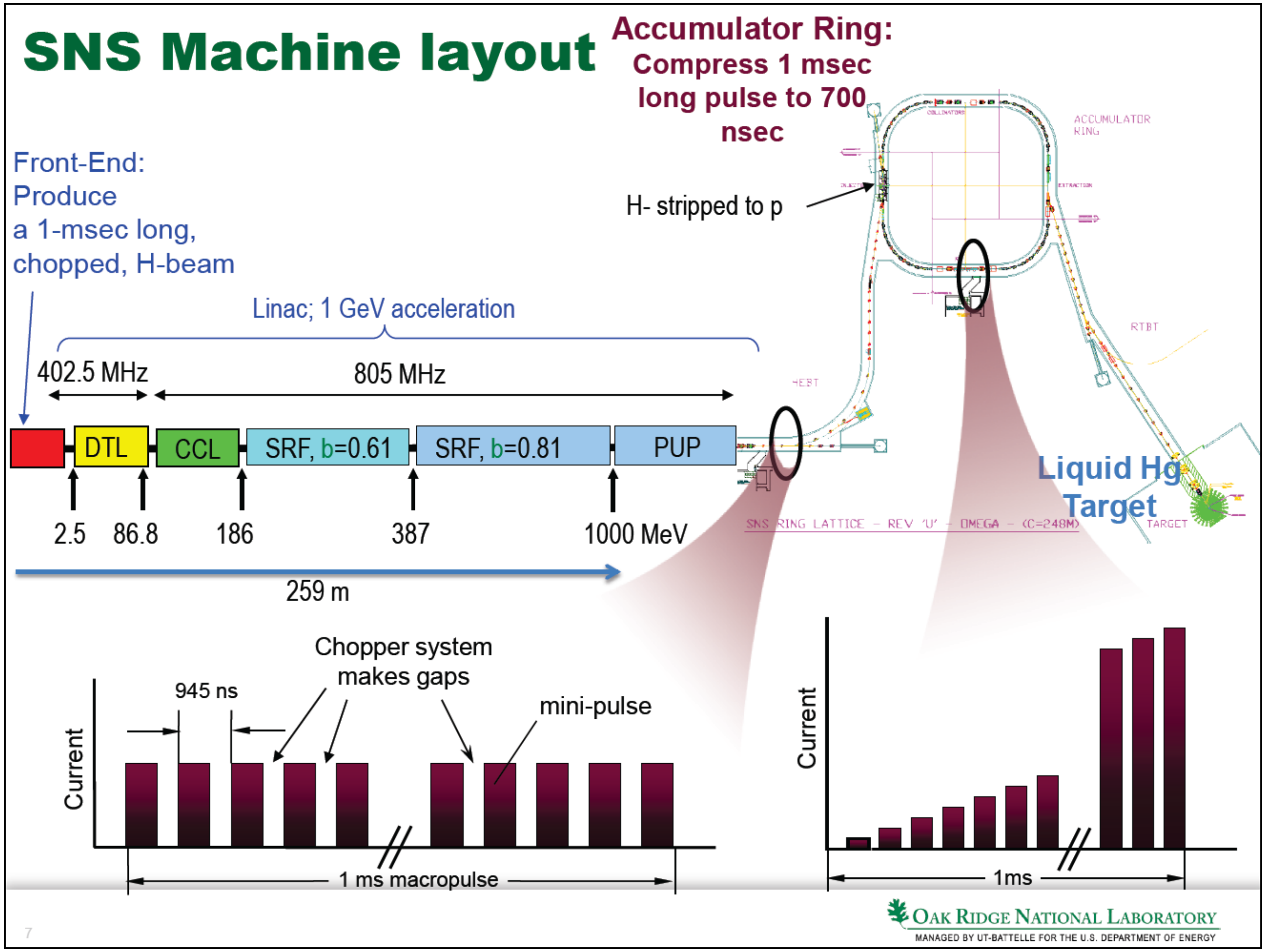
- **SNS = the first high-energy SRF linac for H**
  + the first MW-class one (pulsed but at relatively high DC: 6%)

See S.H. Kim MOP007

- Running well (availability >90%)
- 3 years to ramp the beam power up to 1 MW
- 3 MW upgrade plan (PUP)
  - ✓ 1.3 GeV upgrade
  - ✓ beam current upgrade
  - ✓ @ constant gradients
- Replacement of DTL+CCL by SRF linac is considered

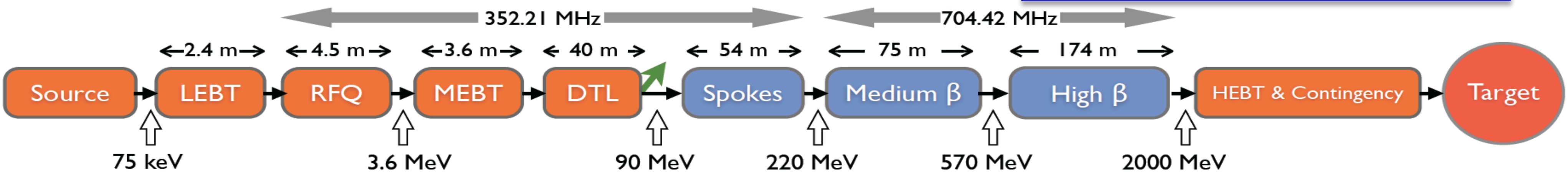
See M.S. Champion MOP002



The ESS @ Lünd

Optimus

See C. Darve MOP004



- **5MW mean power**, pulsed at 4% DC
- Design very similar to SNS, except that CCL is replaced by **SRF spoke cavities**
  - ✓Technological innovation

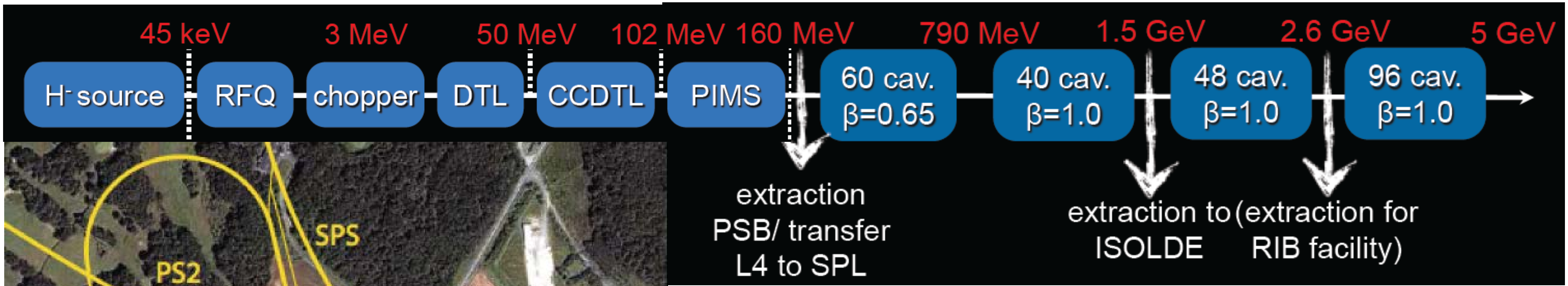
Listen to P. Duchesne FRIOC01

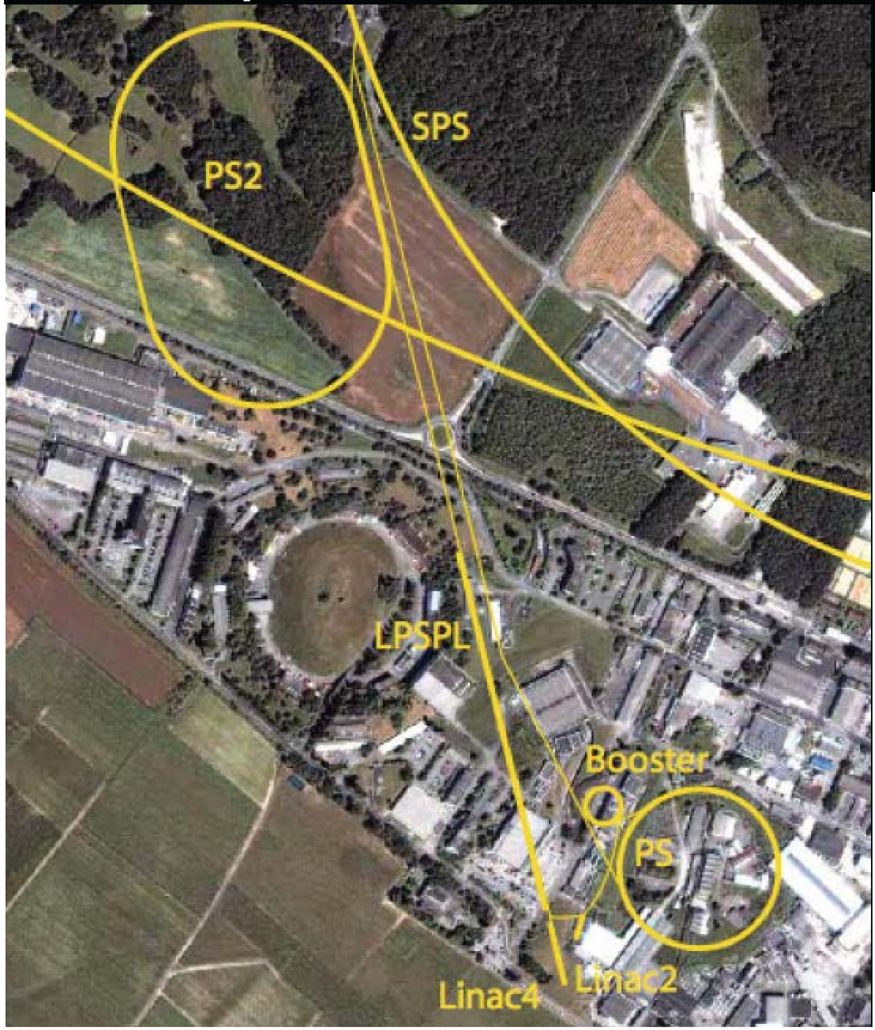
- **“Optimus” 2 GeV new layout to reduce costs**
  - ✓ Higher current (50 -> 62.5mA), same DC
  - ✓ Less cavities (-17 cryomodules)
  - ✓ Higher gradients (+11.25%): E_{pk} = 45 MV/m
- Construction is about to start
- First beam planned in 2019

Listen to G. Devanz FRIOC02

Section	Cavity β	Total number of Modules	Cavity frequency	# Cavity per module	# Cavity per section	Cryomodule length	Section length
Spoke	0.50	13	352 MHz	2	26	~ 2.9 m	54 m
Medium-beta	0.67	9	704 MHz	4	36	~ 6.7 m	75 m
High-beta	0.92	21	704 MHz	4	84	~ 6.7 m	174 m
Total		**43**			**146**		**~ 300 m**

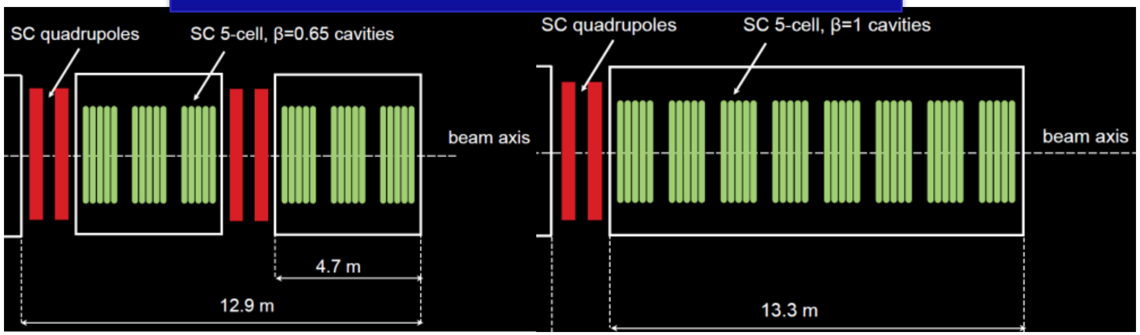
The SPL @ CERN





- **4MW mean power**, pulsed at 2% or 4% DC
- **Linac4 (= SPL front-end) is under construction**
- Linac4 connection to PS is planned in 2016
- SPL status = **R&D on β=1 cryomodule**

Listen to O. Capatina FRIOB04



SNS operational feedback

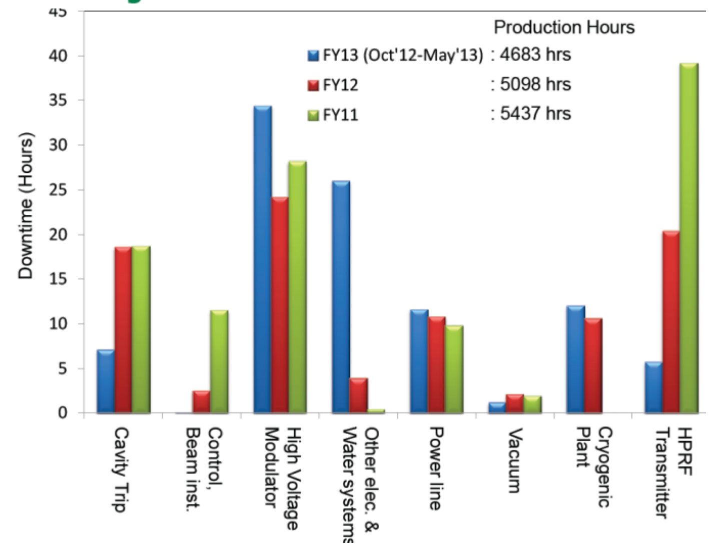
o **Beam losses & SC linac activation**

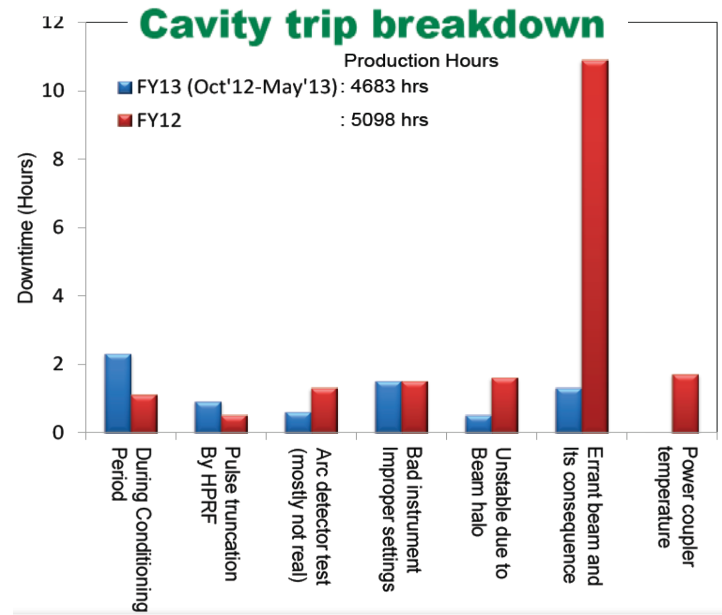
- ✓ Activation is well contained in the SNS, but unpredicted beam losses have been observed
- ✓ Losses recently explained by intra-beam stripping
- ✓ **Use H+ instead of H- if possible !!** (losses /30)

o **SC linac has proven to be substancially more reliable than the NC linac** despite the high number of RF stations & the complexity of cryogenics

- ✓ Less than 1 trip of the SC linac per day
- ✓ Trips dominated by RF systems
- ✓ Trips due to cavities are mainly due to errant beam hitting cavity surface (BLM trips from discharge/arcing in warm linac)
- ✓ Cavity degradation is observed (usually recovered by thermal cycling)
- ✓ Multiple cryomodule repairs in house (coupler window leaks, He & vacuum leaks, tuner failures, HOM couplers…)

SCL system downtime breakdown

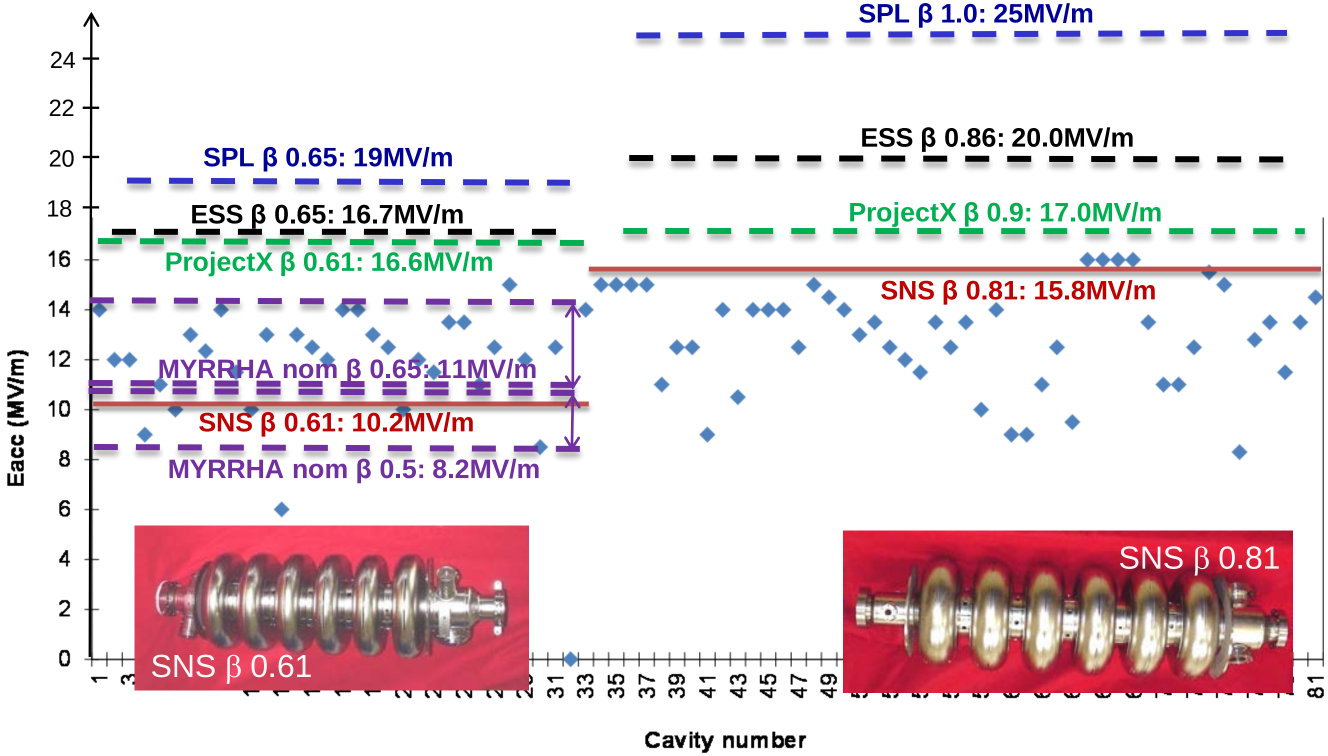


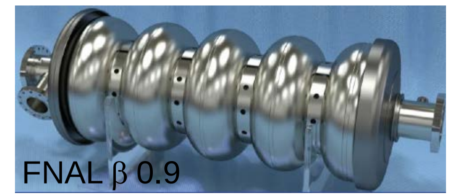


Design constraint #1: Cavity gradients

- **Cavity gradient is directly related to cost** -> tendency to push the gradients
- **SNS experiences a huge gradient variability -> needs for margins & operational flexibility !!**
  - ✓Almost every SNS run, a few cavities have problems, resulting in lower E_{acc} or turn-off -> linac retuning
  - ✓ Achievable gradients are mainly limited by heating by electron activity at high duty factor (especially by induced collective limits)

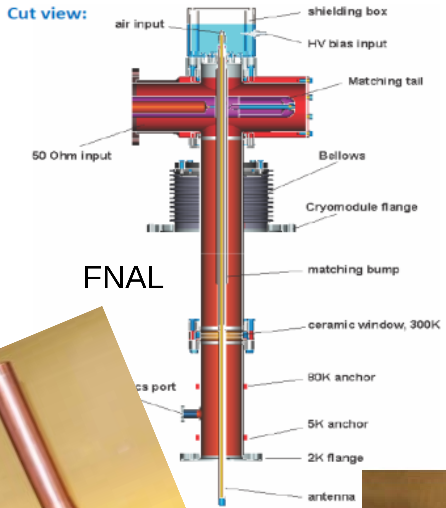
Ex. CM13 individual limits; 19.5, 15, 17, 14.5 MV/m
Ex. CM13 collective limits; 14.5, 15, 15, 10.5 MV/m





Design constraint #2: Power couplers

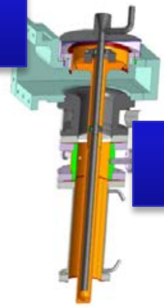
- **The maximal power given by the power coupler to the cavity is a clear limit** for linac designers, especially for pulsed high-current machines
  - ✓ SNS design limit: 550kW peak (48kW average), tested up to 2MW in test stand
  - ✓ SPL design limit: 1.0 MW peak (about 100kW average)
  - ✓ ESS design limit: 1.1MW peak (about 100kW average)



FNAL

- **Most of the high-power couplers design are very similar**
  - ✓ Scaled from the original KEK 508 MHz coupler
  - ✓ Coaxial, single warm window, fixed coupling

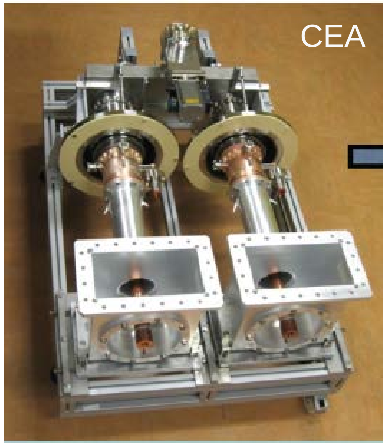
See R. Bonomi THP049



SPL
(air-cooled)

ESS

See E. Rampnoux THP065



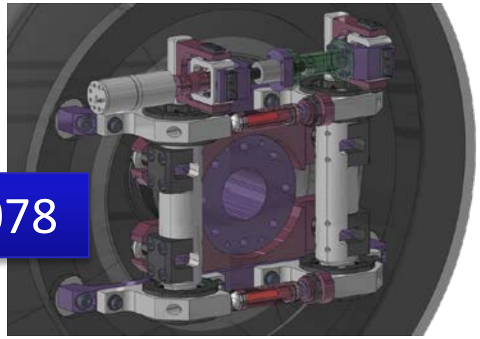
CARE-HIPPI Couplers

- **What about concentrating the R&D effort worldwide on a <u>single design</u> for all machines (1MW pulsed / 100kW CW) ?**
  - ✓ Would be then easier to push the limits towards higher powers (2MW…)

Others

- **HOM couplers are not mandatory** (has become a general agreement)
  - ✓ HOM voltages build-up is naturally damped (thanks to the high HOM frequency dispersion especially)
  - ✓ Simple check that HOM are away from main machine lines (detuning/retuning can help if needed)
  - ✓ **SNS HOM feedthroughs are being taken out**
  - ✓ **No HOM couplers foreseen for ESS, Project X & MYRRHA cavities**

- **Tuners**



See N. Gandolfo THP078

  - ✓ Most of the slow mechanical tuners are based on the CEA Saclay design
  - ✓ Contrary to SNS, **active detuning w/ piezo actuators are a necessity for ESS and SPL**, due to higher gradients and therefore higher Lorentz dynamic detunings

See V. Parma MOP085

- **Cryomodules**
  - ✓ Mostly from CEBAF-like or DESY-style concepts
  - ✓ Innovative solutions are developped (e.g. SPL module)
  - ✓ **Minimize static heat loads** is important **for pulsed machines**
  - ✓ **For CW machines** -> the main concern is to **minimize dynamic heat loads** and therefore **<u>maximise Qo</u>**

See D. Reynet MOP089

See G. Olivier MOP084

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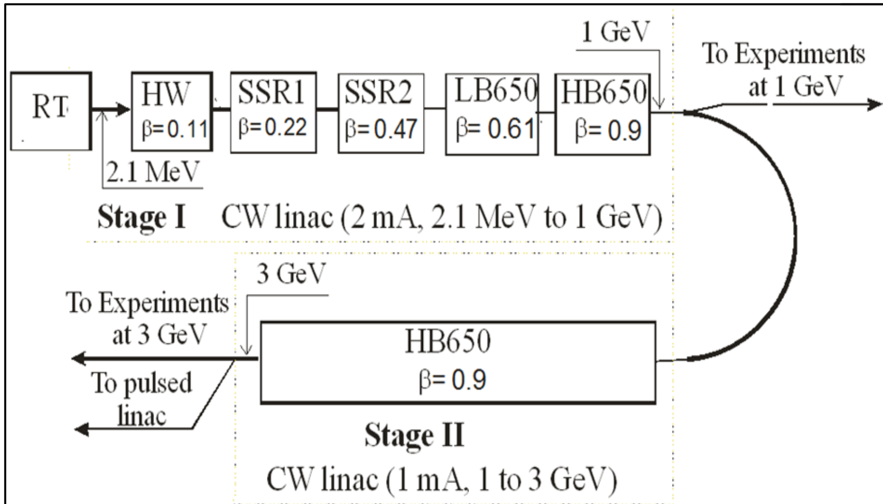
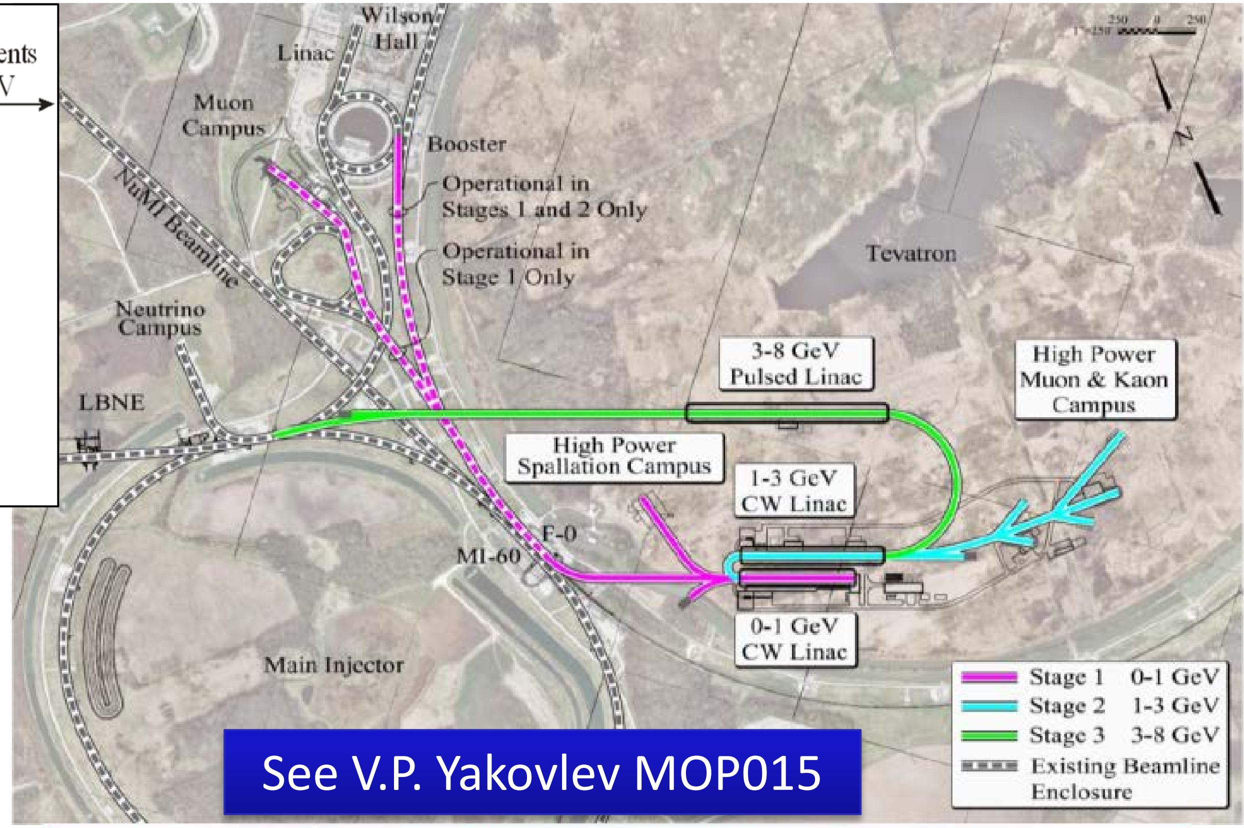
Challenges for CW high power SRF machines

- **Peak beam current is lower but mean beam current is usually higher**
  - ✓ SNS = 1mA, ESS = 2.5mA, MYRRHA = 4mA, C-ADS = 10 mA, IFMIF = 125mA !!
  - ✓ **Beam loss mitigation and MPS management** remain very high concerns
  - ✓ Reinforced by **SC structures at very low energies** ("soft" beam, small apertures, RFQ tails…)
  - ✓ Low peak beam current (except IFMIF) -> lowest RF coupling -> narrowest bandwidth -> **management of microphonics** is to be considered (a 2K bath helps!)
- **CW RF operation**
  - ✓ **Dynamic heat loads** dominates cryogenics -> <u>Qo is an important cost driver</u>
  - ✓ General agreement for **2K operation** down to 350 MHz spoke at least (Project-X, MYRRHA are even fully 2K)
  - ✓ **Thermal issues** on room-temperature elements (couplers, RFQ is non trivial !!!)
  - ✓ **Solid-state amplifiers** when possible !!
- **SC cavities at the RFQ output** (or nearly)
  - ✓ Low-beta SRF (QWR, HWR, spoke…) is not yet very mature for high current beams: the only SC operating cavities with a high current beam are the HWR SARAF ones -> **technology demonstration is required**
  - ✓ **High compactness** is required for SC injectors due to beam dynamics constraints, but compromise is to be found vs operational ease, maintenance, beam diagnostics…

Project-X @ Fermilab





See V.P. Yakovlev MOP015

- 3MW H- beam power at 3GeV
- SRF from 2.1 MeV, 2K operation
- HWR, Spoke, Elliptical
- Main challenge = **demonstration of the SRF injector**

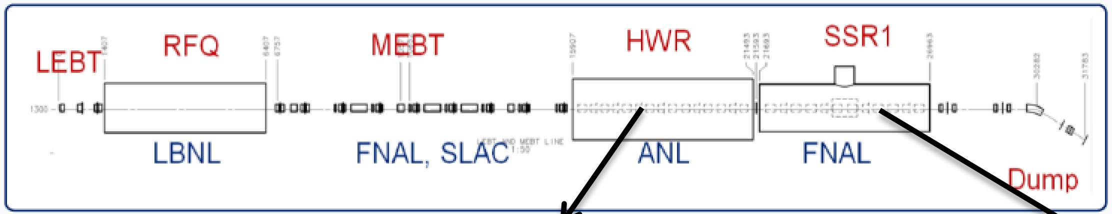
Listen to L. Ristori FRIOB02

Listen to S.S.Som FRIOB03

Section	Freq, MHz	Energy(MeV)	Cav/mag/CM	Type
HWR (β_G=0.11)	162.5	2.1-10	8 /8/1	HWR, solenoid, 5.26m
SSR1 (β_G=0.22)	325	10-32	16 /8/ 2	SSR, solenoid, 4.76m
SSR2 (β_G=0.47)	325	32-160	36 /20/ 4	SSR, solenoid, 7.77m
LB 650 (β_G=0.61)	650	160-520	42 /14/ 7	5-cell ellip, doublet, 7.1m
HB 650 (β_G=0.9)	650	520-3000	152 / 19 / 19	5-cell ellipt, doubl, 11.2m
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 / 28/ 28	9-cell ellipt., quad, 12.6m

The PXIE demonstrator

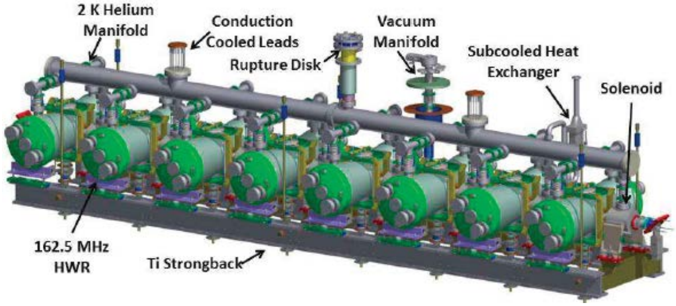
- **Front-end demonstrator PXIE is under construction (25 MeV, 1mA)**
  - ✓ Goal = validate Project X concept & eliminate technical risks (compact lattice layout)
  - ✓ Beam operation planned between 2016 & 2018
  - ✓ Cavities under fabrication

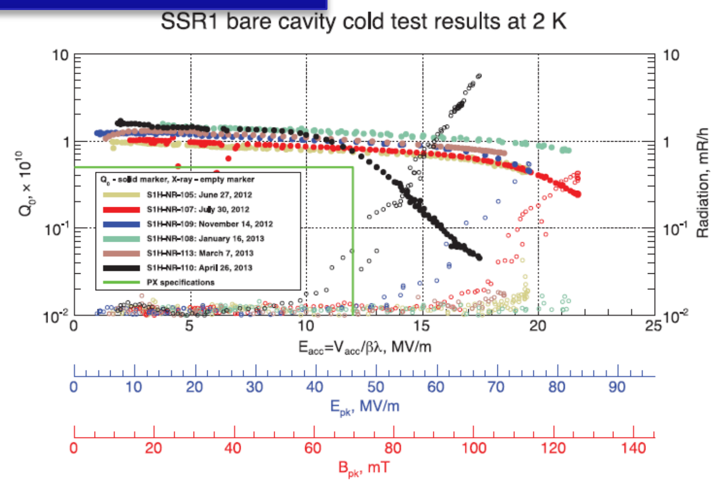


See P. Ostroumov MOP066

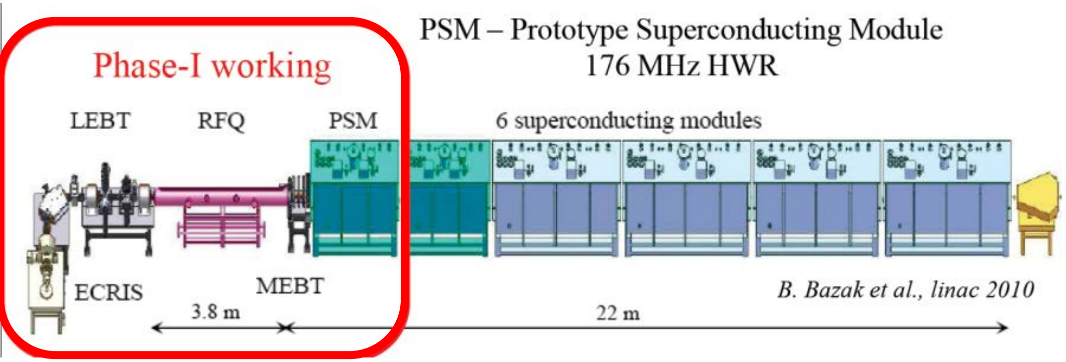
See A.I. Sukhanov MOP014

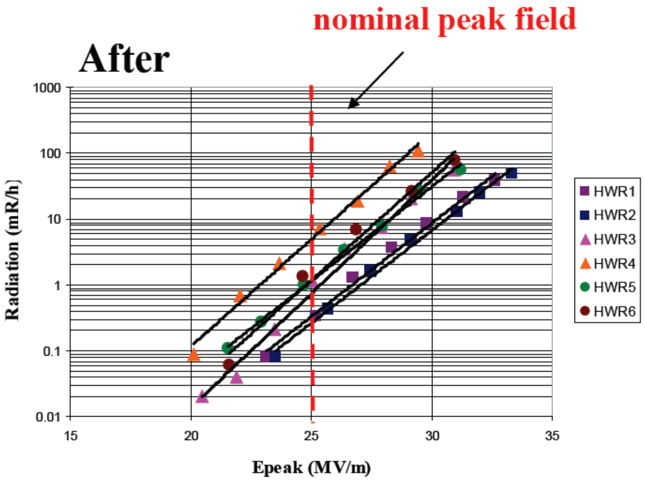
Cavity Type	HWR
Frequency	162.5 MHz
Optimal β	0.112
Effective Length	20.7 cm
Aperture	33 mm
E_{peak}/E_{acc}	4.7
B_{peak}/E_{acc}	5.0 mT/(MV/m)
G	48 Ω
R_{sh}/Q	272 Ω





SARAF status @SOREQ



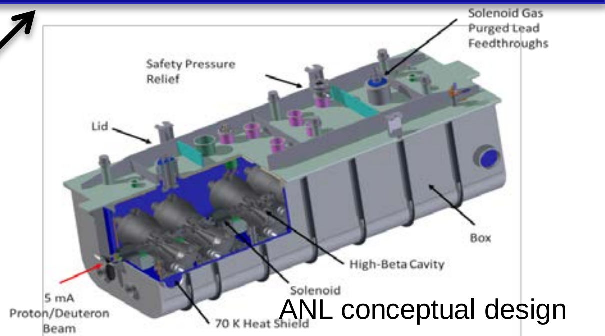


- **Present operation performance**
  - ✓ 1mA CW protons at 4 MeV (2.1mA at 2 MeV)
  - ✓ 4.8 MeV deuterons at 50% dc
- **World first HWR operation** with (high-current) beam !!
- **Main present limitations of the (6 cav) PSM**
  - ✓ **Simultaneous operation of all cavities** at nominal field was not achieved for long period (despite efficient He processing)
  - ✓ Heating of the power couplers (cold window)
  - ✓ Microphonics management & piezo actuators degradation
- **New plan for 40MeV upgrade by 2019** = contract w/ vendor

See J. Rodnizki THP066

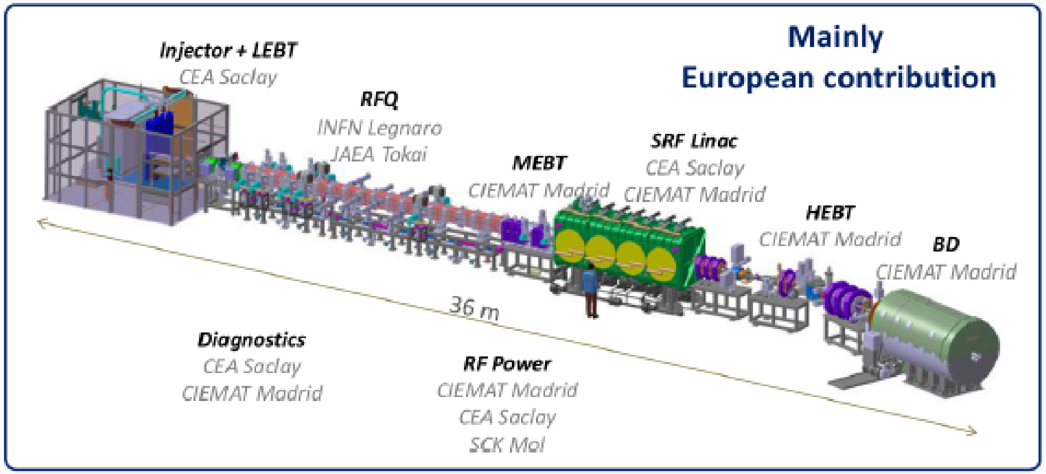
See Y. Bem Aliz MOP056

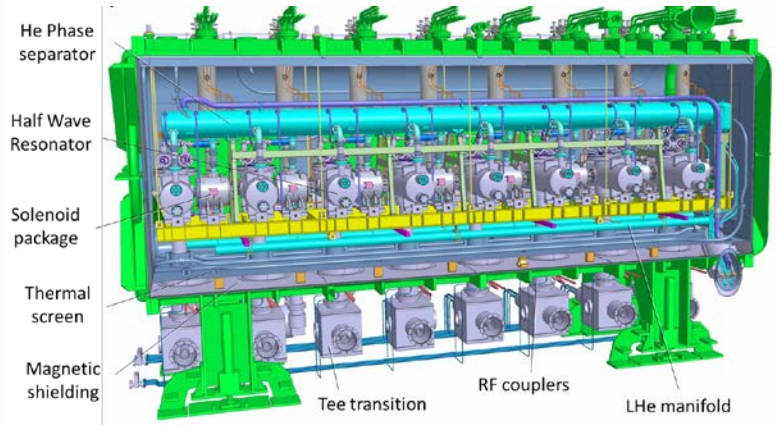
See P. Ostroumov MOP066



ANL conceptual design

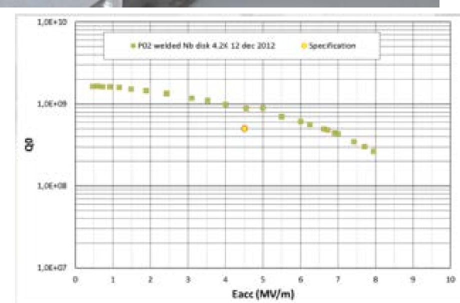
IFMIF and the LIPAC demonstrator



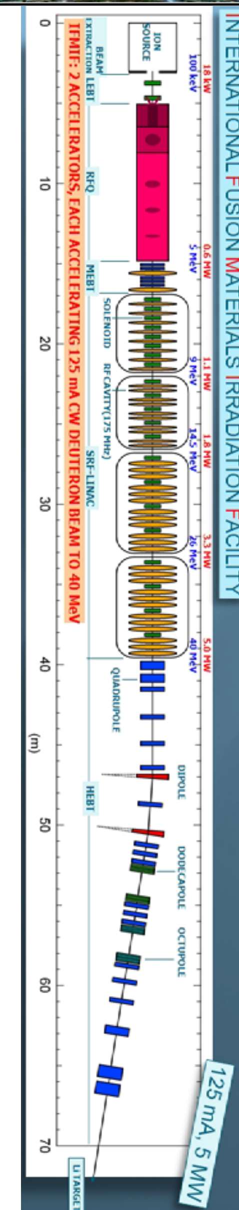


- o **IFMIF** = 5MW D beam (40 MeV, 125mA CW)
- o **LIPAC** demonstrator: 1.1MW (9 MeV, 125mA)
  - ✓ HWR concept similar to PXIE (but 4K)
  - ✓ First beam in 2016
- o **First HWR prototype qualified (VC)**
- o **Additional challenge compared to SARAF/PXIE**
  -> 50 times more beam current !!!
  - ✓ Beam transport tuning, beam losses control…
  - ✓ 70kW CW per cavity !

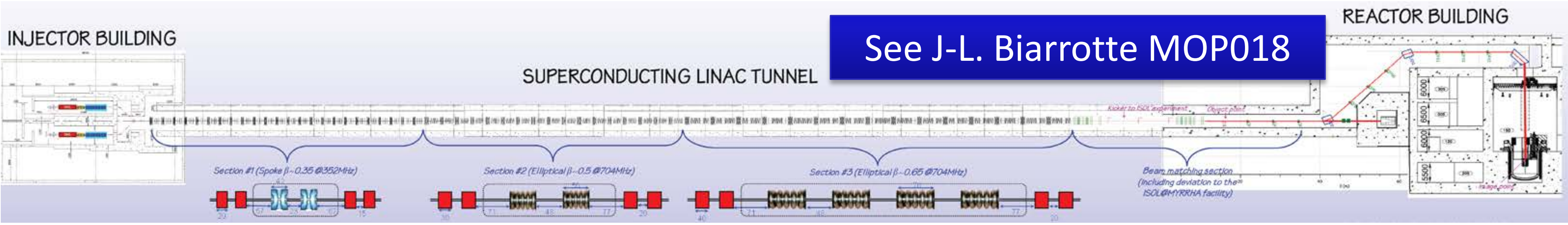
Listen to N. Bazin THIOD03



See H. Jenhani THP056



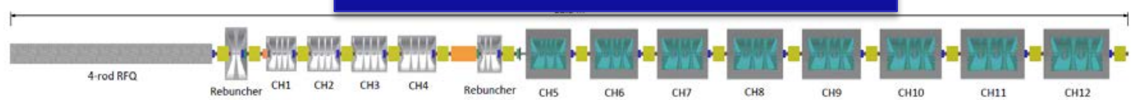
MYRRHA, the European ADS demonstrator



See J-L. Biarrotte MOP018

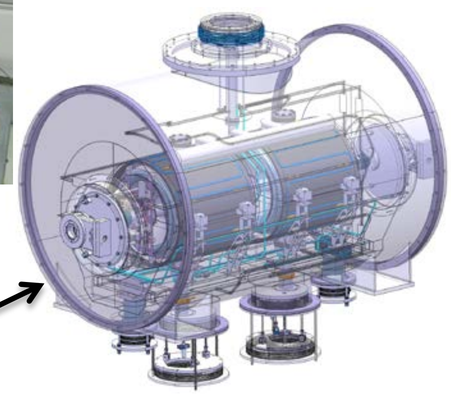
- **2.4 MW cw proton beam @600 MeV**
  - ✓ Decision for construction 2015

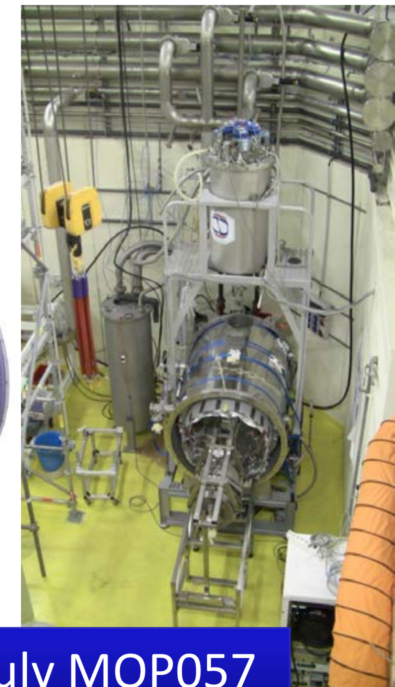
See D. Mäder MOP065



- **Specific additional challenge = Reliability** (i.e. avoid beam interruptions)
- **Redundant & compact injectors** (based on CH cavities)
- **R&D on fast fault-recovery schemes**
  - ✓ Compensate RF faults in main linac (<3sec)
  - ✓ Margins required on operation points
  - ✓ Fast piezo-based tuners
- **R&D on main SRF components:** CH, spokes, elliptical

See M. Bush THP003



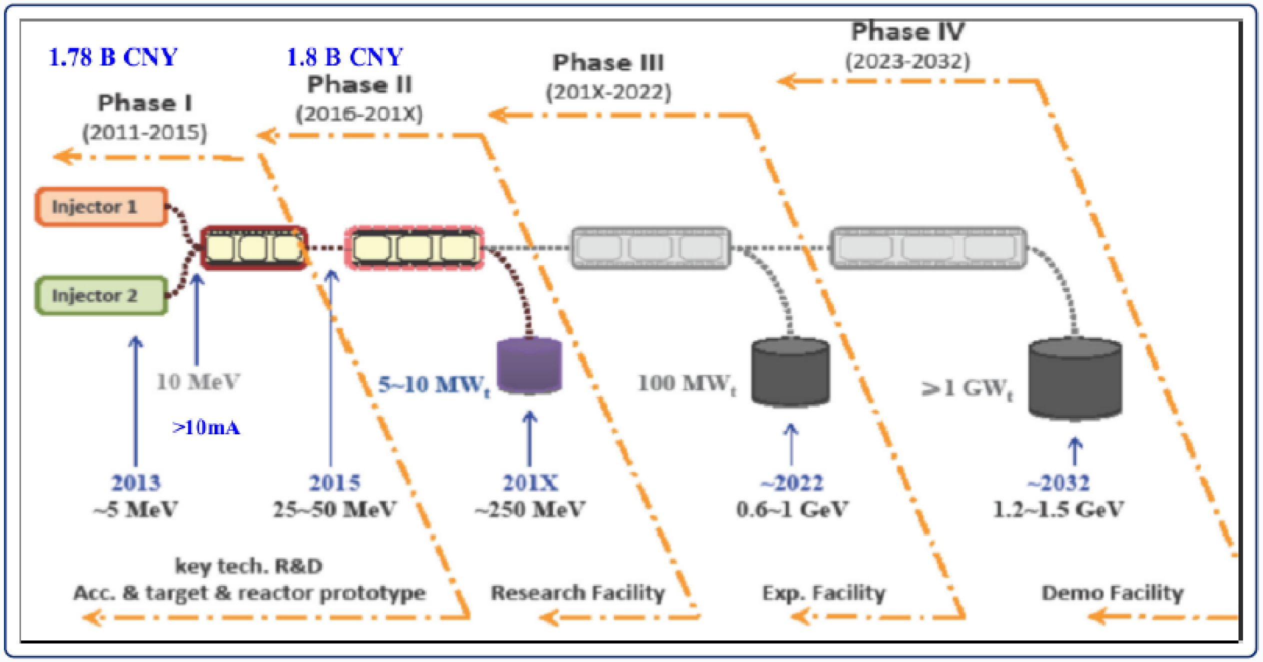


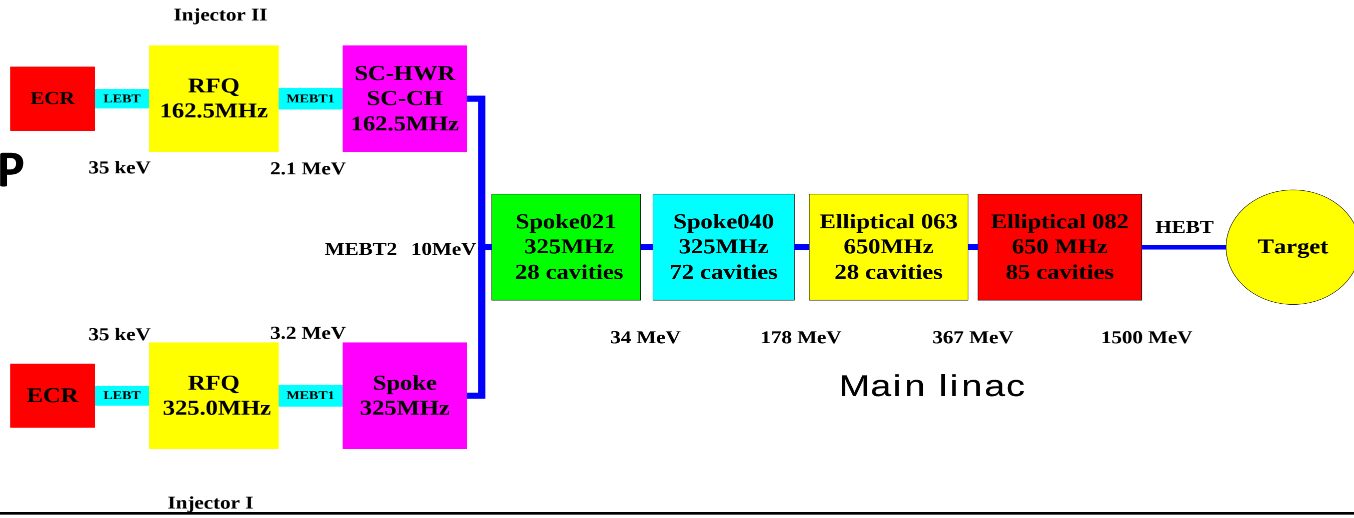
See F. Bouly MOP057

Chinese-ADS

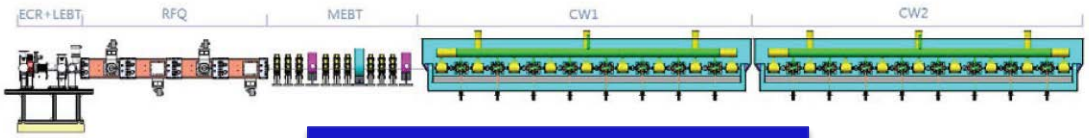
- **Very ambitious ADS program**
  - ✓ Injectors by 2015
  - ✓ ~ 1 GeV by 2022
  - ✓ ~ 15 MW ADS by 2032
- **Same chosen reliability-oriented concepts as MYRRHA**
  - ✓ Redundant injector
  - ✓ Fault tolerance in main linac
- **Based on FNAL/ILC frequency**
- **Active R&D on SRF, especially the 2 front-ends @IMP & @IHEP**

Listen to Y. He THIOD01





Chinese-ADS SRF activities



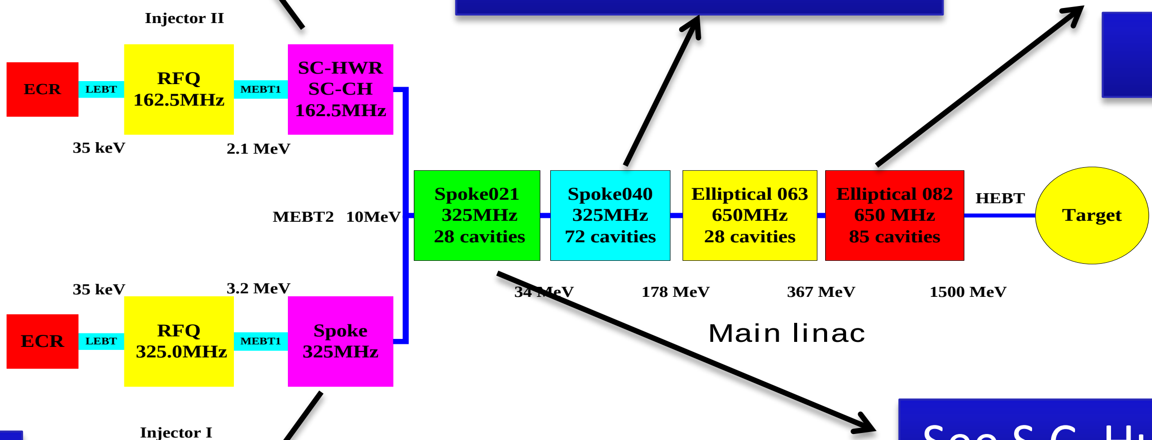
See S. He THP081

Table 1: Main Parameters of HWR Cavity

f (MHz)	162.5
Gb	0.09
Ra/Qo (Ohm)	148
Qo	1.40E9 at 4.4K
Epeak (MV/m)	25
Uacc (MV)	0.78
Operating temp. (K)	4.4-4.5
Operating pressure (bara)	1.20-1.25
Volume of Lhe container (Liter)	18.3
Static heat load (W)	~0.9
Dynamic heat load (W)	12
Coupler cooling flow (W)	Ghe cooled,12L/min under standard condition

See P. Sha THP028

See S. Jin THP017

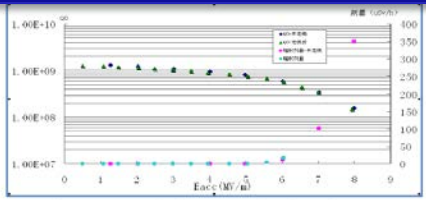


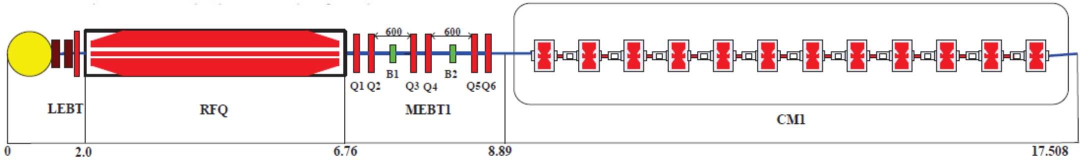
See H. Li THP022

See X. Chen THP050

See S.C. Huang THP015

See Z.Q. Li THP021





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4. Summary

Summary (personal view)

- High-power H/D accelerators have been made feasible thanks to SRF
- More & more SRF machines & projects, especially CW with SRF from RFQ on
- **2000-2030 will clearly be the "golden age" for SRF high-power linacs**

  -> Enjoy ! *before new technologies appear (e.g. plasma acceleration)*
- **Present main R&D challenges**
  - ✓ High gradients for pulsed machines (ESS, SPL)
  - ✓ Demonstration of SRF-based injectors is required (PXIE, SARAF, LIPAC)
  - ✓ Piezo-actuators base tuners become a necessity; reliability is to be improved
- **Clear & high potential for synergies & collaborations**
  - ✓ R&D on HWR and spoke cavities
  - ✓ Potential for common cavity and/or cryomodule designs (e.g. ESS/SPL/MYRRHA elliptical 0.65)
  - ✓ Potential for a common high-power coupler design to overtake the present 1MW pulsed limit
  - ✓ ADS R&D to improve reliability can be a potential benefit to all future projects
  - ✓ Solid-state amplifiers revolution

TY for your attention and…

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- …sorry for all possible mistakes & omissions…

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