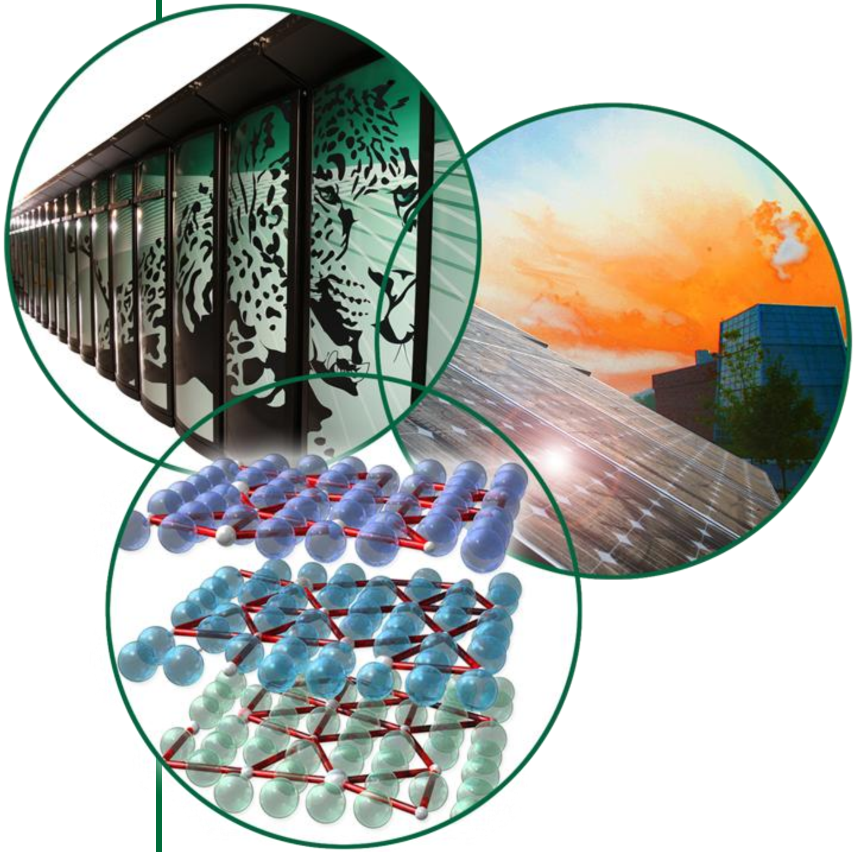
Advances in SRF for Neutron Sources



SRF 2011

Chicago

July 25-29, 2011

Sang-ho Kim

SNS/ORNL

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Acknowledgements

- Special THANKS to
  - Alban Mosnier (CEA/Scalay, France)
  - Yuan He (Chinese Academy of Science, China)
  - Stephen Molloy (ESS, Sweden)
  - Satishi Joshi (RRCAT, India)
  - Jean-Luc Biarrotte (IPN/Orsay, France)
  - Phillip Ferguson, John Galambos, Charles Peters (ORNL)
  - Project-X (FNAL)
  - And many others…

Neutron Scattering for future R&D

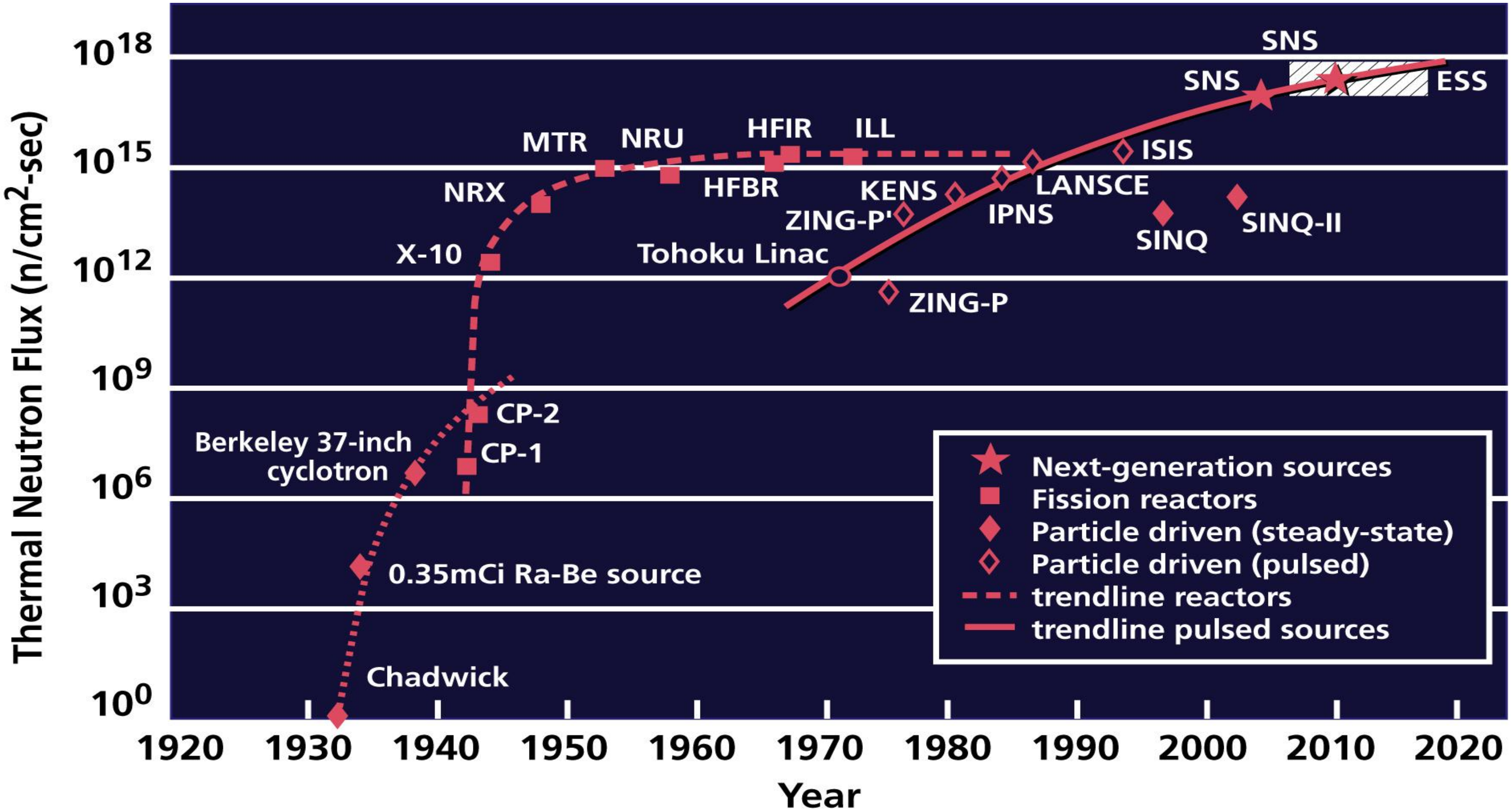
- **Micro-focused beams spatially resolved to <1 micron**
- **Dynamics at time scales from <1 ps to minutes**
- **Length scales from angstroms to ≥1000 nm**
- **Measurements of transient phenomena on time scales of 10 ms**
- **Neutron imaging with sub-micron spatial resolution**

IPNS (ANL):	50 MeV linac + 500 MeV Sync.,	10 kW,	0.33 kJ/pulse,	4e12 protons/pulse
LANSE (LANL):	800 MeV linac + acc. Ring,	80 kW,	7 kJ/pulse,	5e13 protons/pulse
ISIS (RAL):	70 MeV linac + 800 MeV Sync.,	160 kW,	3.2 kJ/pulse,	2.5e13 protons/pulse
SNS (ORNL):	1 GeV SC linac + acc. Ring,	1.4 MW,	24 kJ/pulse,	1.5e14 protons/pulse
(ESS (EU):	2.5 GeV SC linac,	5.0 MW,	350kJ/pulse,	2.1e15 protons/pulse)

Neutron Sources

Reactors have reached the limit at which heat can be removed from the core

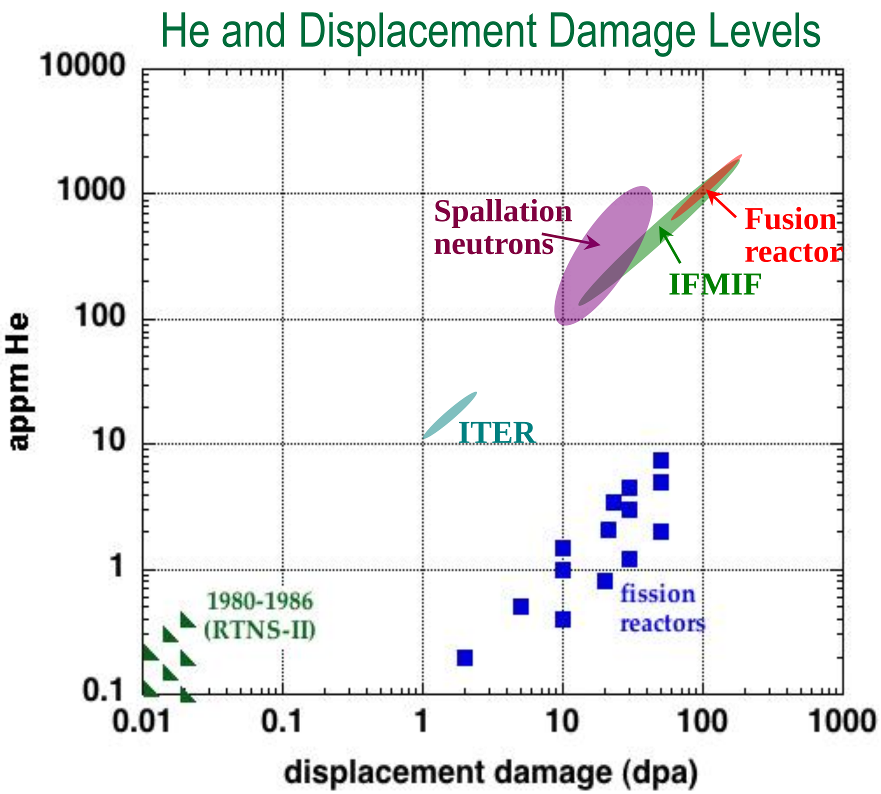
Pulsed sources have not yet reached that limit and hold out the promise of higher intensities

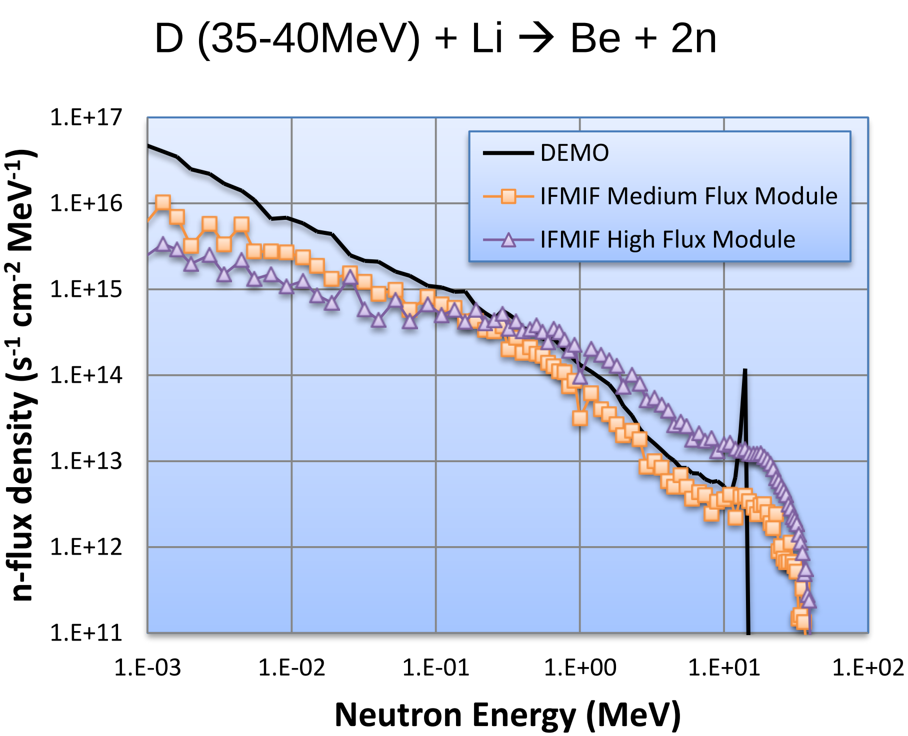


(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

Fusion Material testing

- High neutron flux (>5 × 10^{14} n/cm^2-s, *E* > 1 MeV) to explore basic radiation damage phenomena to doses of 100 dpa or higher
- Capability for in situ measurements
- Fusion-relevant irradiation: 14 MeV neutrons, ~10 appm He/dpa, up to ~200 dpa)





Sources: R. J. Kurtz and G. R. Odette, Major Materials Challenges for DEMO
Harnessing Fusion Power Workshop, Los Angeles 2009

Accelerator Driven System (ADS)

- **Nuclear Transmutation**
  - **HLW (Minor actinide/long lived fission products)→ reduce radio-toxicity and amount of long-lived nuclear wastes**
  - **Fertile material (U238, Th232)→ fissile material (Pu239, U233)**
- **Energy production**
  - **Driving fission chain reactions in sub-critical reactor**
- **Comments on ADS in 90's (accelerator aspects)**
  - **Too expensive (real estate gradient~1MV/m)**
  - **Availability & trip rate are inadequate for ADS**
- **Present**
  - **Linac length: 1/3~1/5 (thank to the RF technology) than studies in 90's**
    - **Real estate gradient: SNS (5 MV/m), ESS (8.4 MV/m), MYRRHA (2.75 MV/m)**
  - **Study on trip rate: achievable**
  - **Active R&D and studies in many countries**

NRC (1996), Nuclear Wastes: Technologies for Separations and Transmutation
DOE report (1999), A Roadmap for developing Accelerator Transmutation of Waste Technology
DOE white paper (2010), Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

High power proton linac studies using SRF technology (started in 90's)

- **APT**
- **ATW**
- **ESS**

6th SRF workshop 1993, CEBAF, Newport News, VA, USA

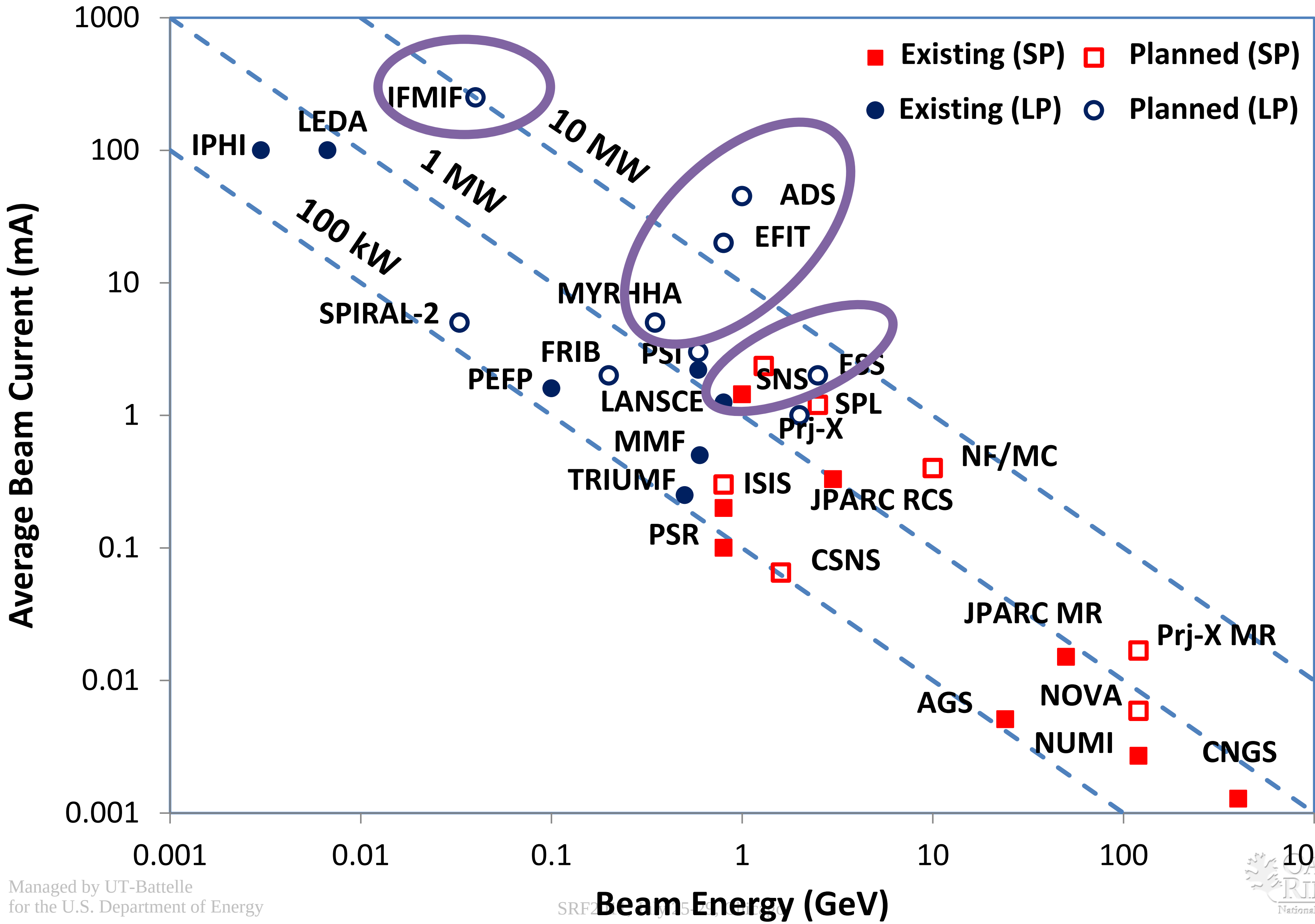
Superconducting Cavities for Neutron Spallation Sources and other High Intensity Proton Accelerators

H. Lengeler
CERN Geneva, Switzerland
and
European Spallation Source
KFA Jülich, Germany

A b s t r a c t:

High intensity linear proton or deuteron accelerators are at present intensively studied for applications in pulsed spallation sources, for fusion material research and for nuclear waste transmutation. Superconducting cavities could offer an interesting option for high intensity linacs. The specific merits and the requirements for their use are reviewed and illustrated by the proposal of a 5 MW pulsed European Spallation Source and by a CW linear accelerator considered at Los Alamos for nuclear waste transmutation.

Beam Power Frontier for ion beam accelerators



Why SRF has become a technology of choice

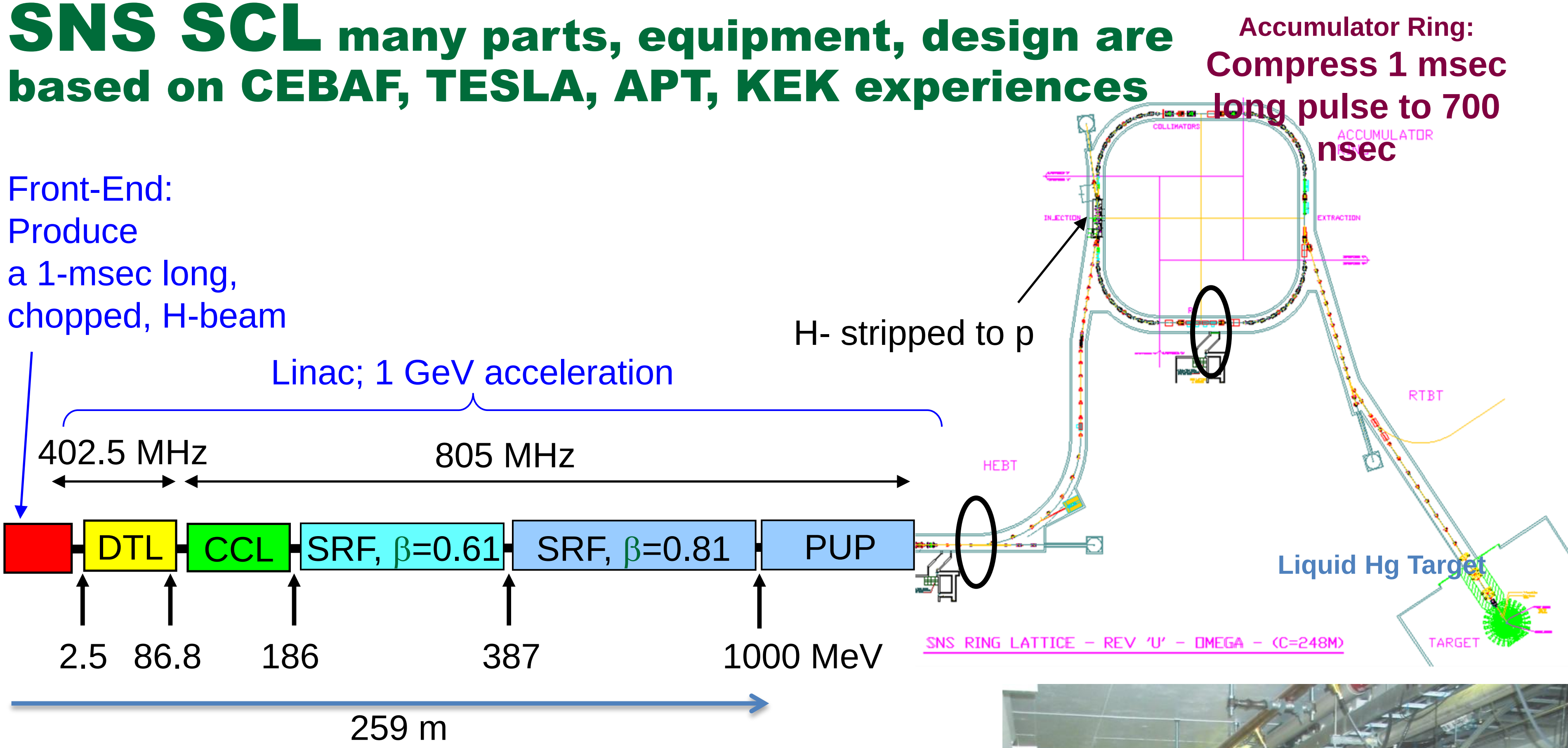
For both CW and Pulsed

- Lower activation ← larger bore size, UHV
- Operational flexibility
- Higher efficiency as duty factor goes higher
- Short linac length
- Only possible option for the beam power > several MW

Superconducting Linac Architecture

- Choice of RF structure: cavity types, betas, no. of groups
- Choice of RF frequency: structure, available RF power sources
- What gradient can be reliably achieved in practice?
  peak fields, technology
- Beam: loss, dynamics
- Choice of NC/SC transition energy: trend pushes lower
- Lattice type: solenoid or quadrupole focusing? Cold or warm magnet?
- No. of cavities/cryomodule
- Warm to cold transitions? Warm or cold instrumentation? Cryogenic segmentation: parallel cryogenic feed from a transfer line, or interconnected cryomodules?
- Operating temperature: 2K or not 2K?
- Extract Higher-Order-Mode power or not?
- Other parts/equipment availability

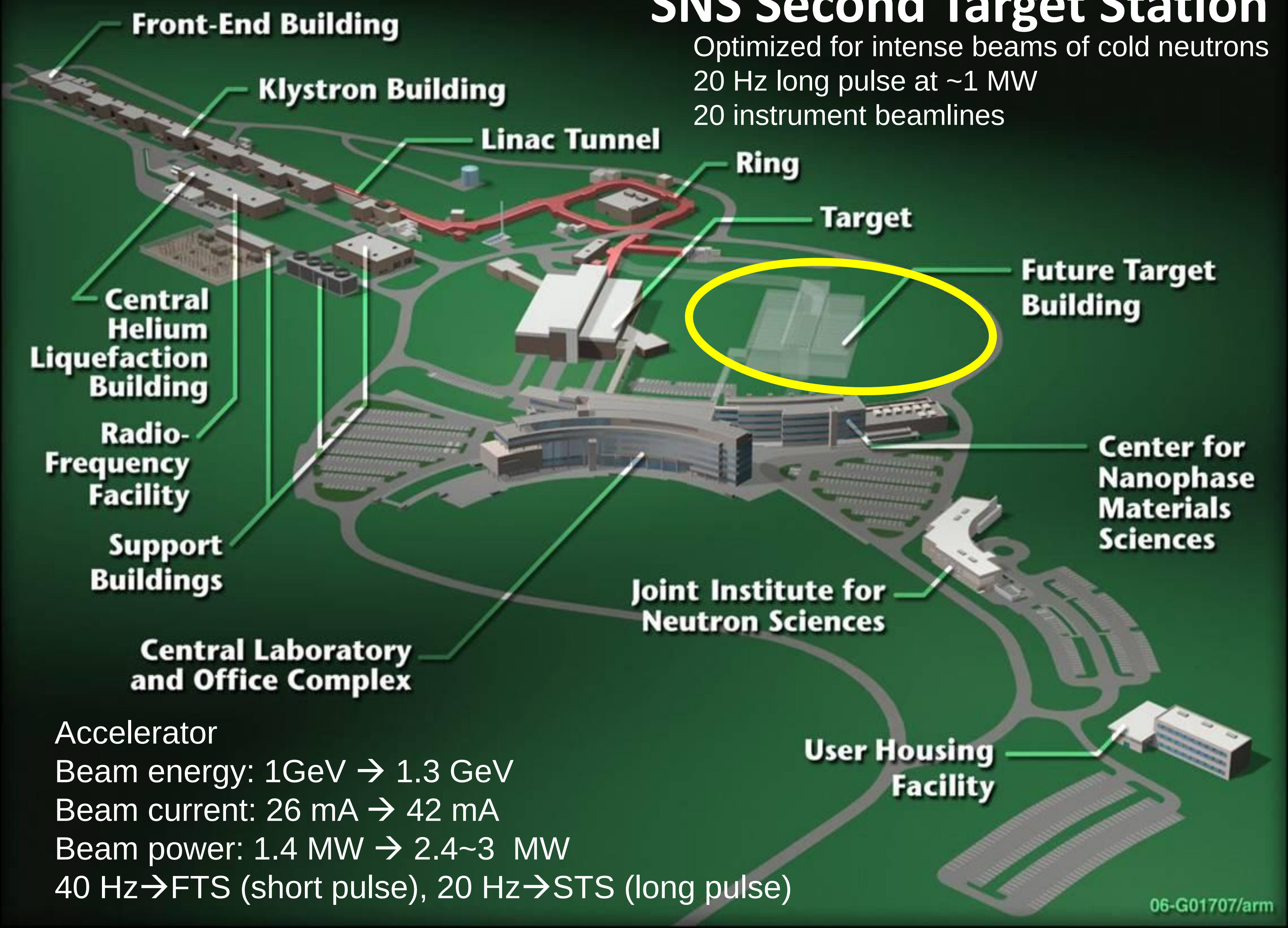
SNS SCL many parts, equipment, design are based on CEBAF, TESLA, APT, KEK experiences



- **World's first high-energy superconducting linac for protons**
- **157-m long, 81 independently-powered 805 MHz SC cavities, in 23 cryomodules**
- **71-m long Space is reserved for additional cryomodules to give 1.3 GeV**

SNS Second Target Station

Optimized for intense beams of cold neutrons
20 Hz long pulse at ~1 MW
20 instrument beamlines



Accelerator
Beam energy: 1GeV → 1.3 GeV
Beam current: 26 mA → 42 mA
Beam power: 1.4 MW → 2.4~3 MW
40 Hz→FTS (short pulse), 20 Hz→STS (long pulse)

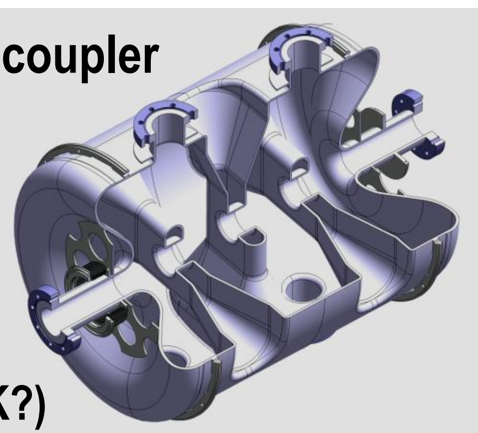
ESS

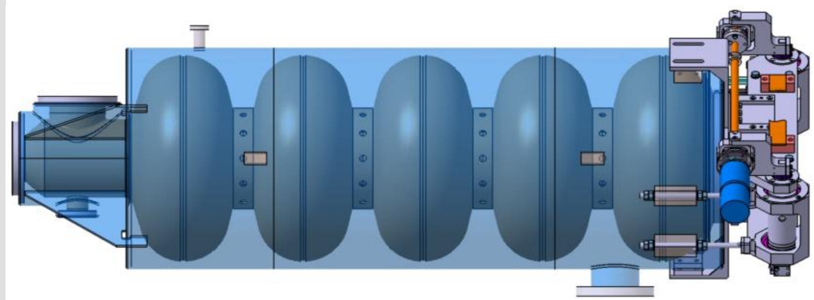
(Courtesy of Stephen Molloy, ESS)

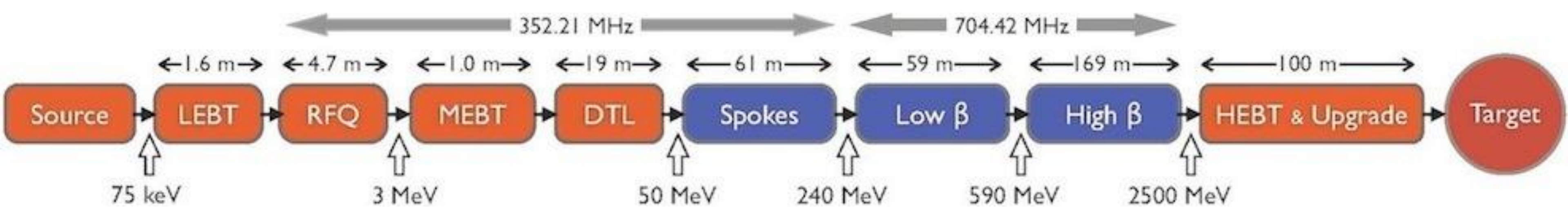
- **Proton Beam: 5 MW, 2.5 GeV, 2.86ms, 14 Hz, Long pulse**
- **RF frequency 352/704 MHz**
- **Uncontrolled beam loss<1W/m,**
- **Availability>95%**

- β=0.62 & 0.95, E_{acc} = 15 MV/m
- Power couples
  - 1 MW peak, 10% duty cycle
  - RF & mechanical study
  - Thermal/cooling study
  - Compatible with any upgrade scenario
- Cryomodule
  - Mechanical, cryo, & vacuum design
- Prototypes & testing

- E_{acc}=8 MV/m
- High peak power in the coupler
- ~400 kW nominal
- Pulsed operation
- Microphonics
- Open questions:
  - HOMs?
  - Operation temp. (2K or 4K?)
  - Cryomodule layout



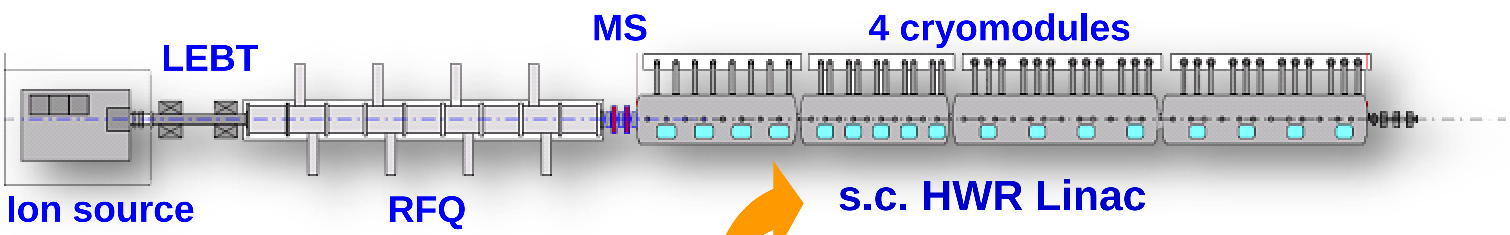




IMFIF

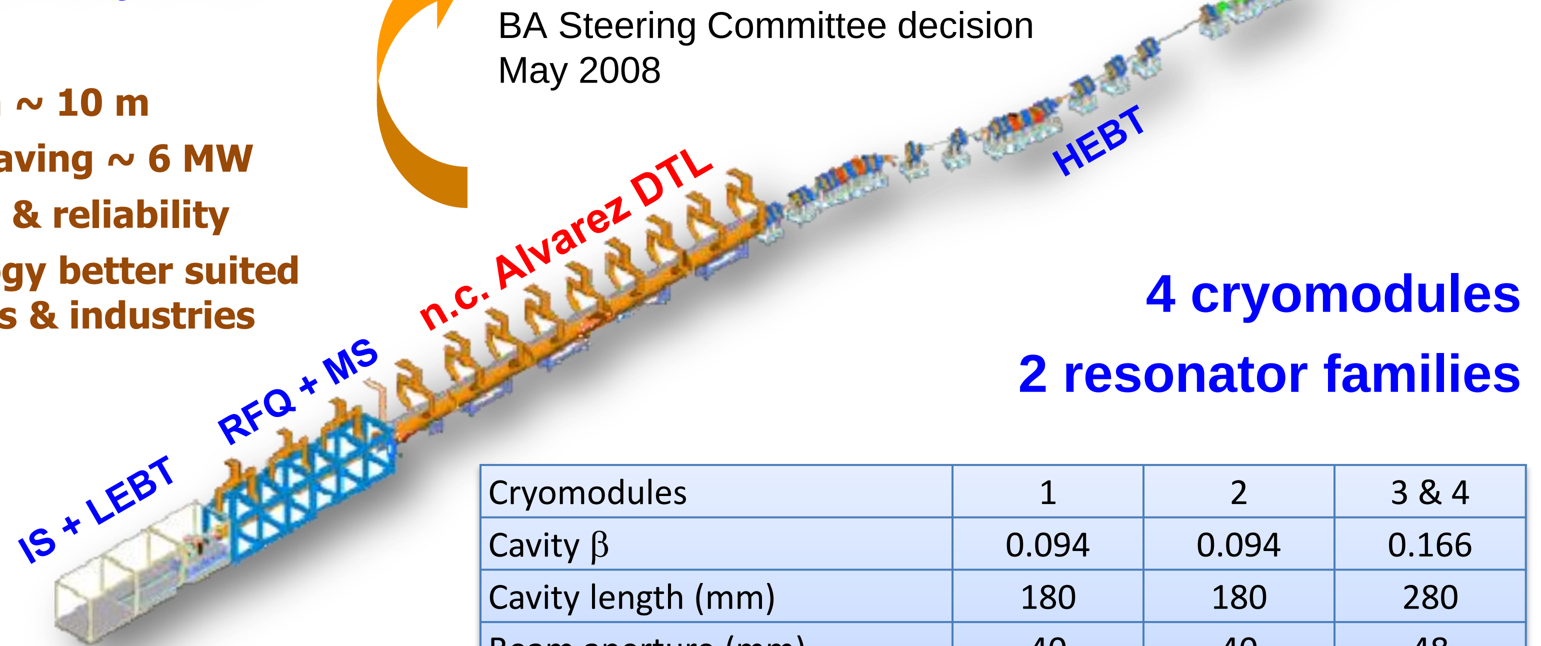
(Courtesy of Alban Mosnier, CEA)

n.c. Alvarez DTL replaced by SRF (HWR) Linac



s.c. HWR Linac

BA Steering Committee decision
May 2008



Advantages

- **length reduction ~ 10 m**
- **operation cost saving ~ 6 MW**
- **higher flexibility & reliability**
- **mature technology better suited to existing teams & industries**
- **less sensitive to machining & assembly errors**

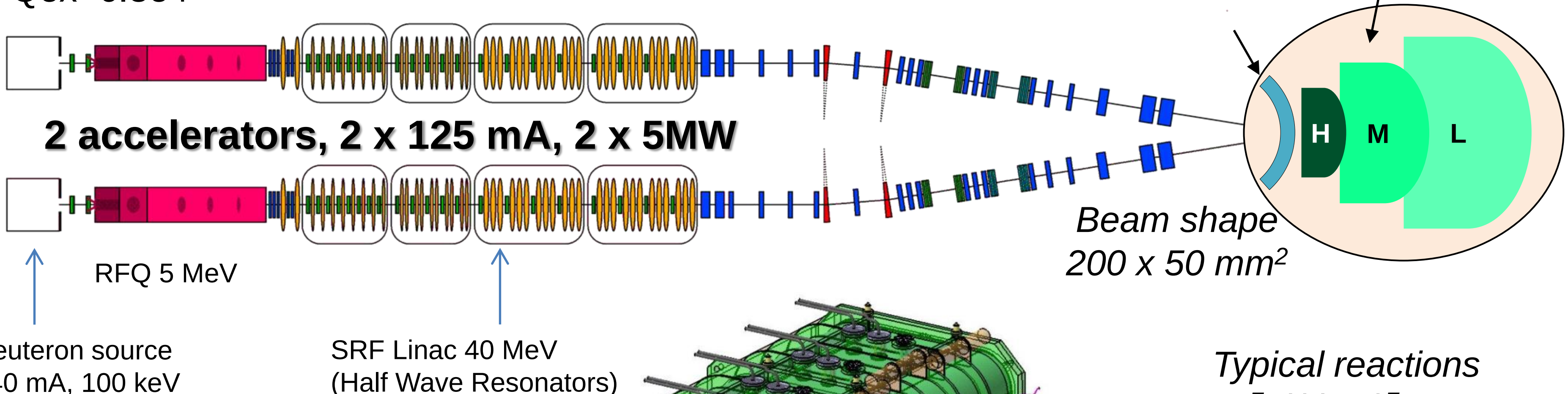
4 cryomodules

2 resonator families

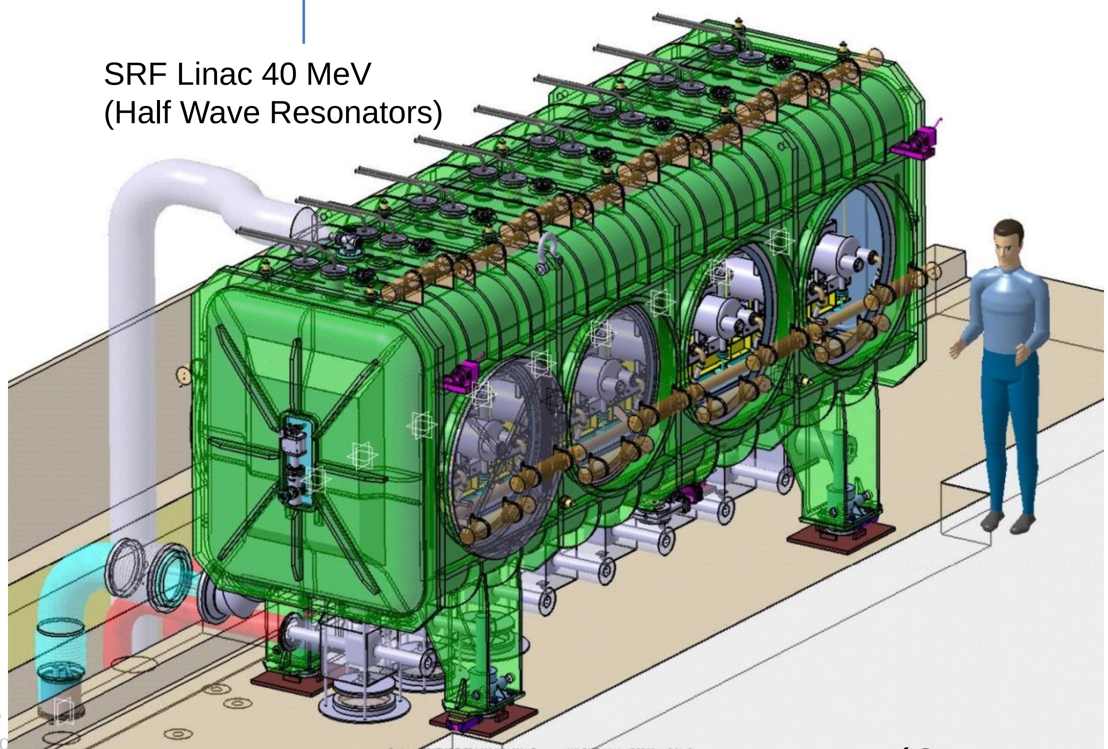
Cryomodules	1	2	3 & 4
Cavity β	0.094	0.094	0.166
Cavity length (mm)	180	180	280
Beam aperture (mm)	40	40	48
Nb cavities / cryostat	1 x 8	2 x 5	3 x 4
Nb solenoids	8	5	4
Cryostat length (m)	4.64	4.30	6.03
Output energy (MeV)	9	14.5	26 / 40

Cryomodule under construction for the accelerator prototype
The first one of the IFMIF SRF Lianc~5 m Long
4.5 MV/m, reliability, limits the coupler power
Large beam aperture 40-48 mm
Qex=6.3e4

High	>20 dpa/y,	0.5 L
Medium	> 1 dpa/y,	6 L
Low	< 1 dpa/y,	> 8 L



Typical reactions
$^7Li(d,2n)^7Be$
$^6Li(d,n)^7Be$
$^6Li(n,T)^4He$



(Courtesy of Alban Mosnier, CEA)

EU-ADS

(Courtesy of Jean-Luc Biarrotte, IPN, Orsay)

- **(EU) ETWG report on ADS, 2001**
- **(EU-FP5) PDS-XADS project (2001-2004)**
- **(EU-FP6) EUROTRANS programme (2005-2010)**
- **MYRRHA Project (Multi-purpose hYbrid Research Reactor for High-tech Applications at Mol (Belgium): ADS demonstrator to be operational in 2023, 2.5 mA 600 MeV CW**
- **Industrial transmuter (EFIT): ~20 mA, 800 MeV**

MYRRAH (Courtesy of Jean-Luc Biarrotte, IPN, Orsay)

Main features of the ADS demo

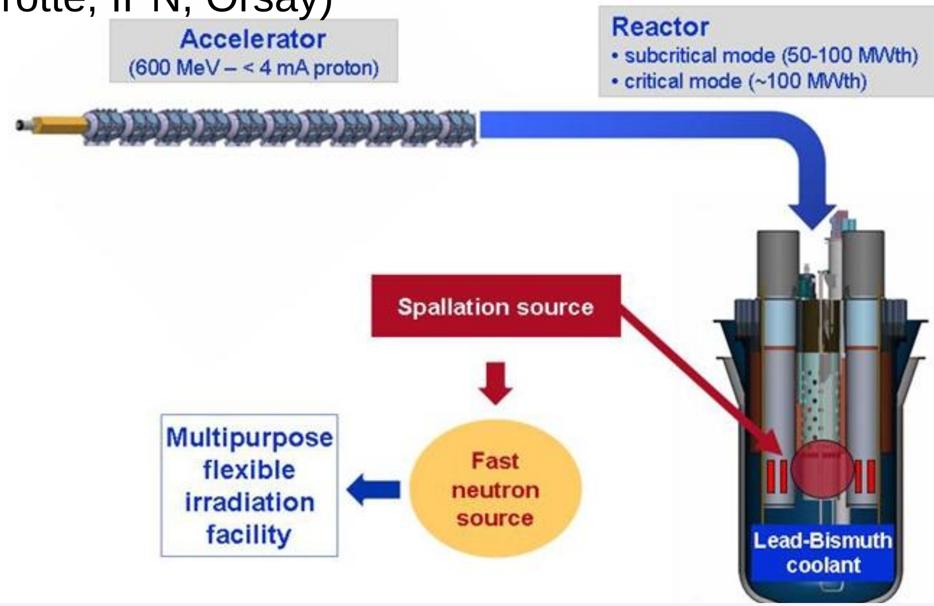
~70 MWth power

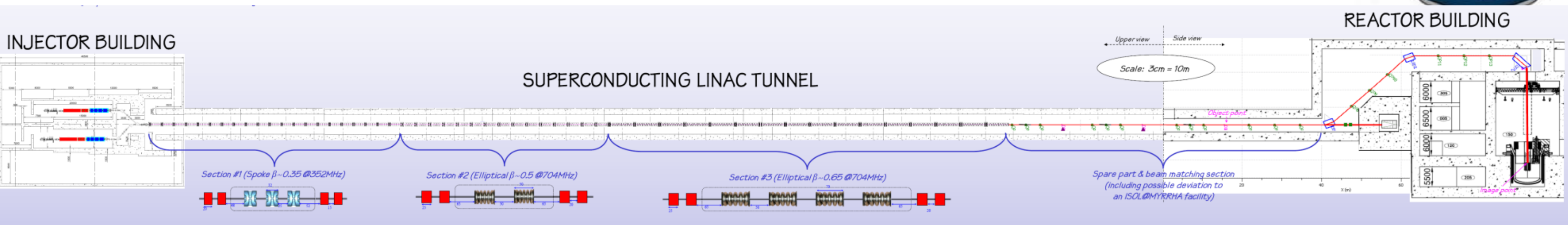
k_{eff} around 0.95

600 MeV, 4 mA proton beam

Highly-enriched MOX fuel

Pb-Bi Eutectic coolant & target





Independently-phased SC linac

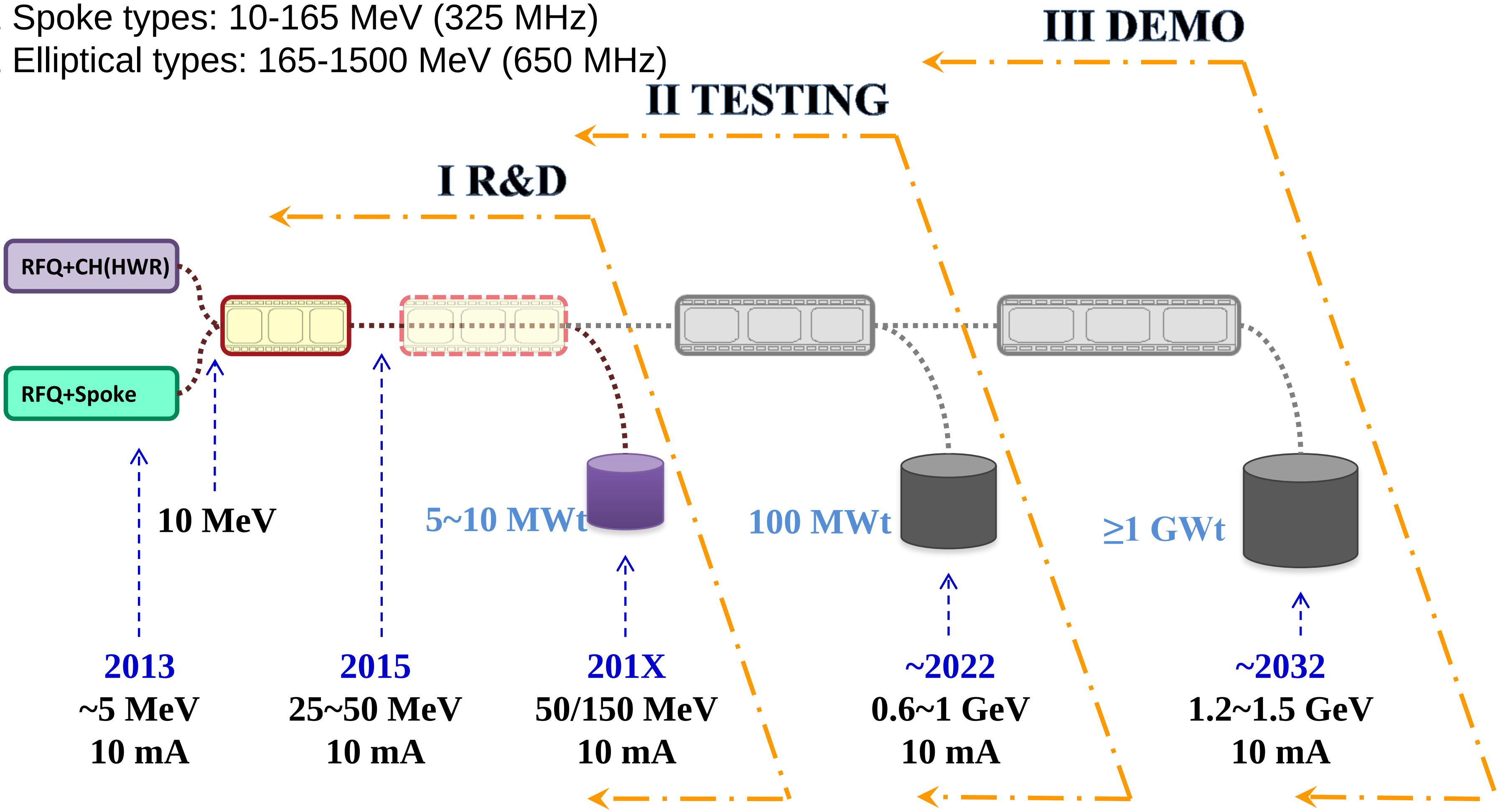
- 352 MHz spoke & 704MHz elliptical
- low gradients, fast fault-tolerance capabilities expected

Section number	1	2	3
Input energy (MeV)	17.0	86.4	186.2
Output energy (MeV)	86.4	186.2	605.3
Cavity technology	Spoke 352.2 MHz	Elliptical 704.4 MHz	
Cavity geometrical β	0.35	0.47	0.66
Cavity optimal β	0.37	0.51	0.70
Nb of cells / cavity	2	5	5
Focusing type	NC quadrupole doublets		
Nb of cavities / cryomodule	3	2	4
Total nb of cavities	63	30	64
Acc. field (MV/m @ opt. β)	5.3	8.5	10.3
Synchronous phase (deg)	-40 to -18	-36 to -15	
5mA beam loading / cav (kW)	1 to 8	3 to 22	17 to 38
Section length (m)	63.2	52.5	100.8

Chinese-ADS load map

Courtesy of Yuan He, Chinese Academy of Science

2 Spoke types: 10-165 MeV (325 MHz)
2 Elliptical types: 165-1500 MeV (650 MHz)



C-ADS is being developed by CAS. IHEP and IMP are in charge of proton accelerator. The facility is dedicate for transmutation and subcritical reactor. The project will be three stages. It is for technology R&D in the first 5 ~ 7 years.

Indian-ADS

Ongoing Indian activities in ADS program

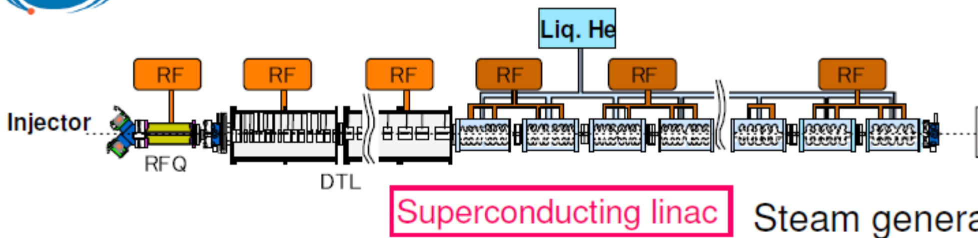
- Design studies of a 1 GeV, 30 mA proton linac.
- Development of 20 MeV high current proton linac for front-end accelerator of ADS.
- Construction of LBE experimental loop for design validation and materials tests for spallation target module.
- Development of computational tools and data for neutronics of spallation target and coupled sub-critical reactor.
- Experimental validation of reactor physics codes and data with 14-MeV neutrons in sub-critical core at PURNIMA labs.
- Design studies for ADS reactor applications.

From S. Banerjee (BARC), Thorium utilization for sustainable supply on nuclear energy at 1st international workshop on Accelerator driven sub-critical systems & thorium utilization, 2010

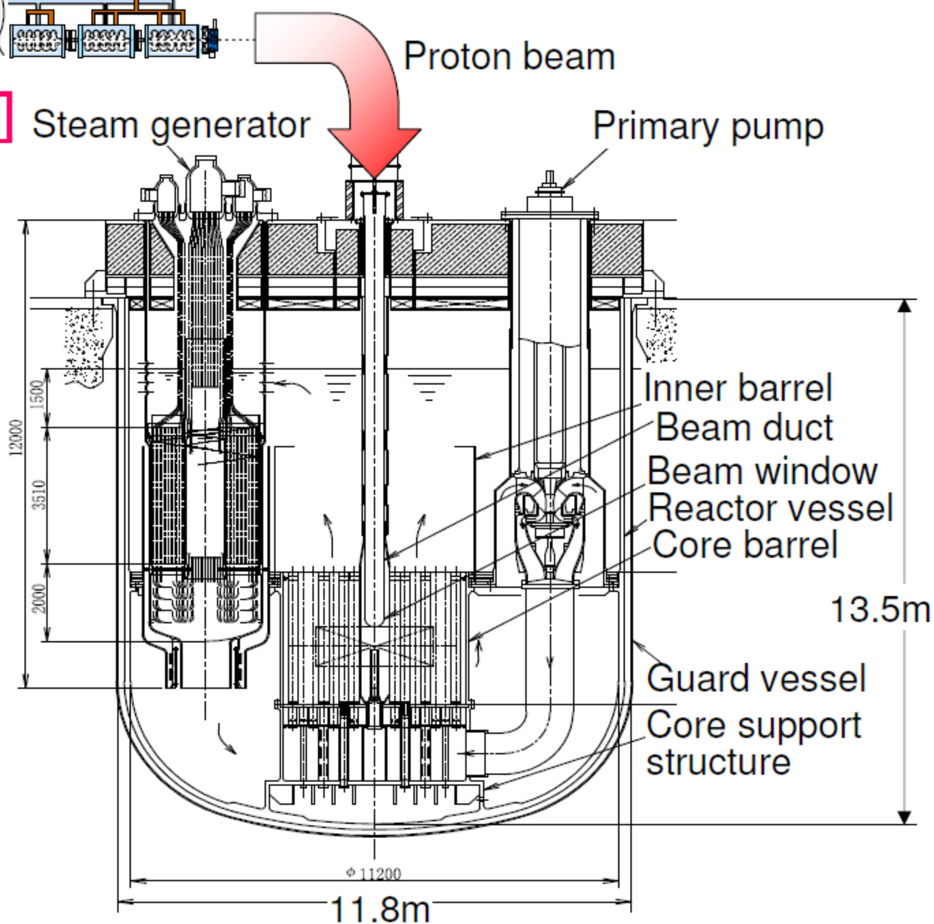
Japanese-ADS

Hayanori Takei, Research and Development Programme on ADS in JAEA at AccApp '09/IAEA

***Conceptual Design** of Future ADS*

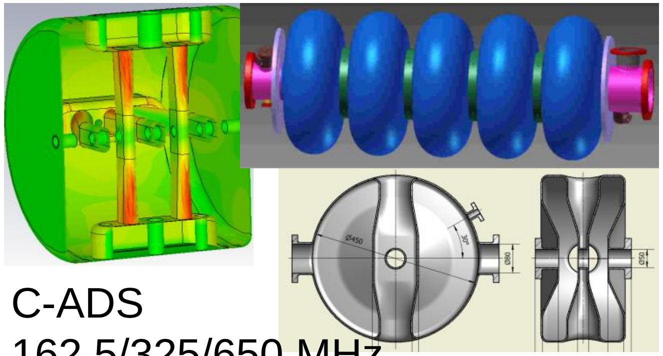


- Beam energy : 1.5 GeV
- Max. beam current : 20 mA
- Klystron : 972 MHz, 750 kW (cw)
- # of klystrons : 89
- Spallation target : Pb-Bi
- Coolant : Pb-Bi
- Max. k_{eff} = 0.97
- Thermal output : 800 MWt
- MA initial inventory : 2.5t
- Transmutation rate :
  10%MA / Year
- 600EFPD, 1 batch

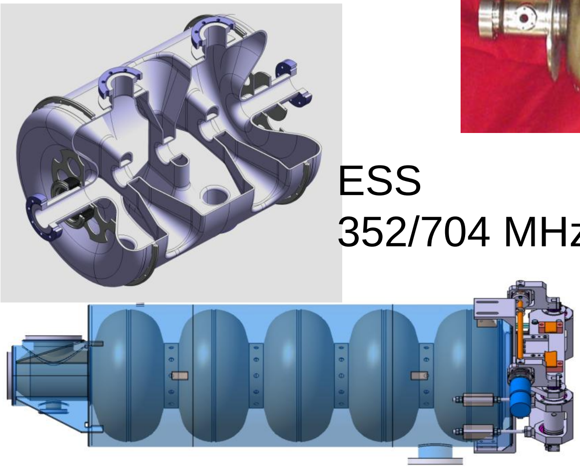


SRF Cavities

SNS
805 MHz

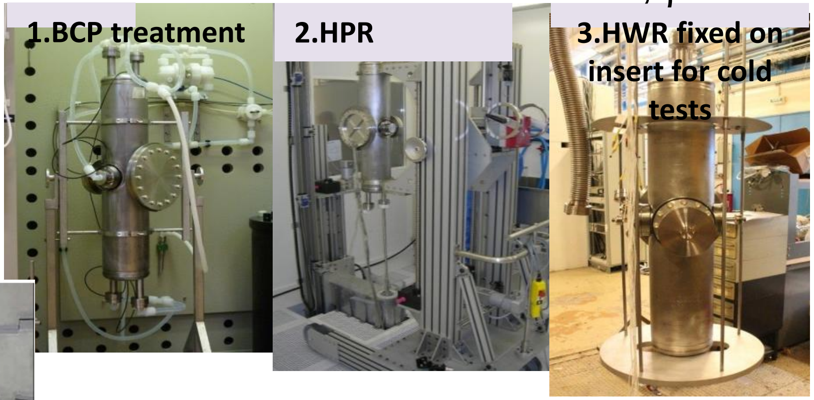


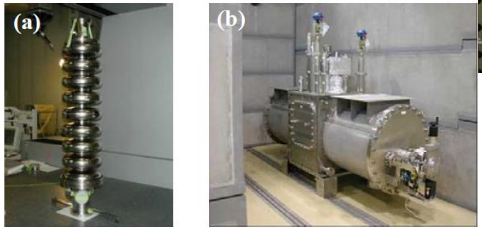
C-ADS
162.5/325/650 MHz



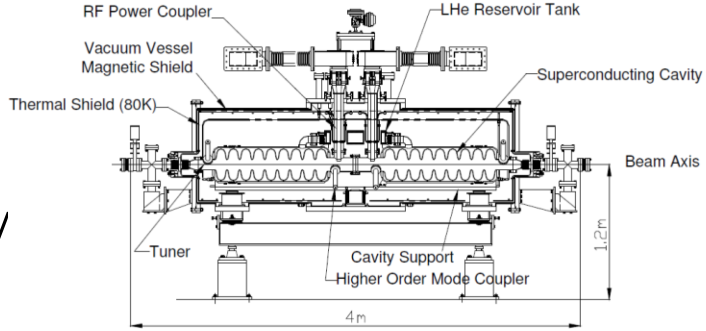
ESS
352/704 MHz

IFMIF HWR 175 MHz, β=0.094

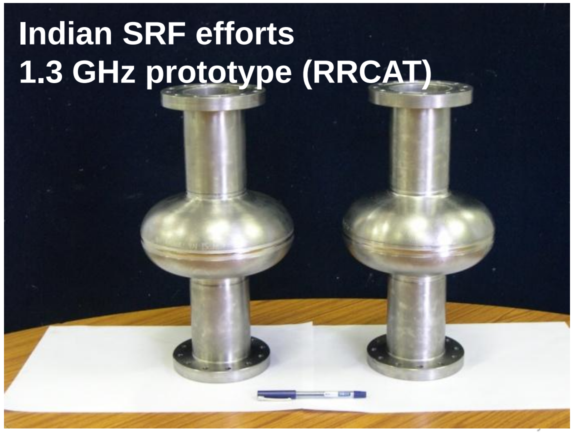




J-ADS, 972 MHz



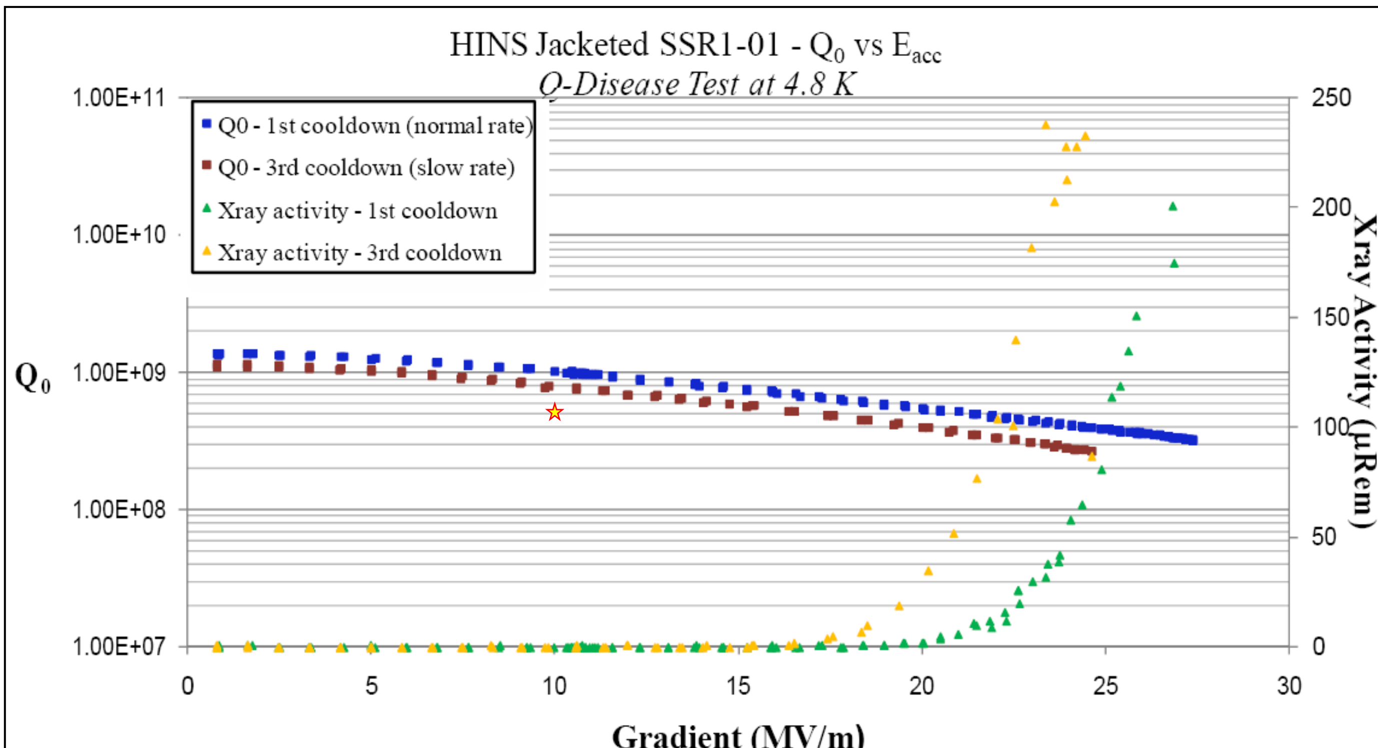
MYRRHA
352/704 M



SRF cavities

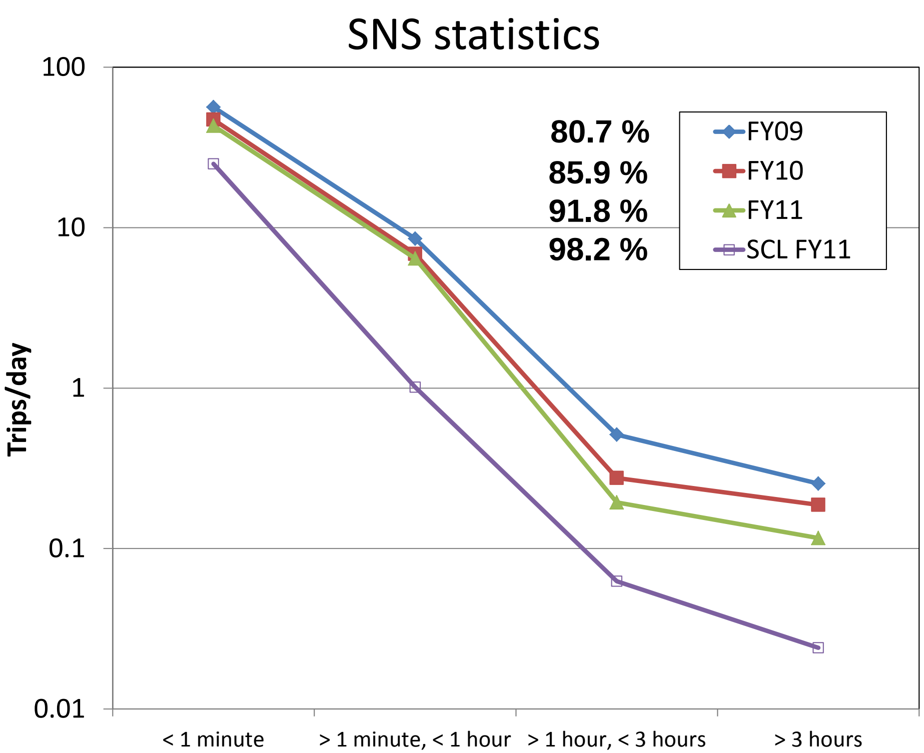
- Choices: Peak beam current, geometric beta, duty factor, reliability, cavity type, RF frequency, experiences, etc.
- Spoke cavities: typical design gradient 8~12 or higher MV/m
  - Starts showing good results
  - Cryomodule prototyping efforts are on-going in many labs.
- Elliptical cavities: typical design gradient 10~20 MV/m

(Courtesy of Mark Champion, FNAL)

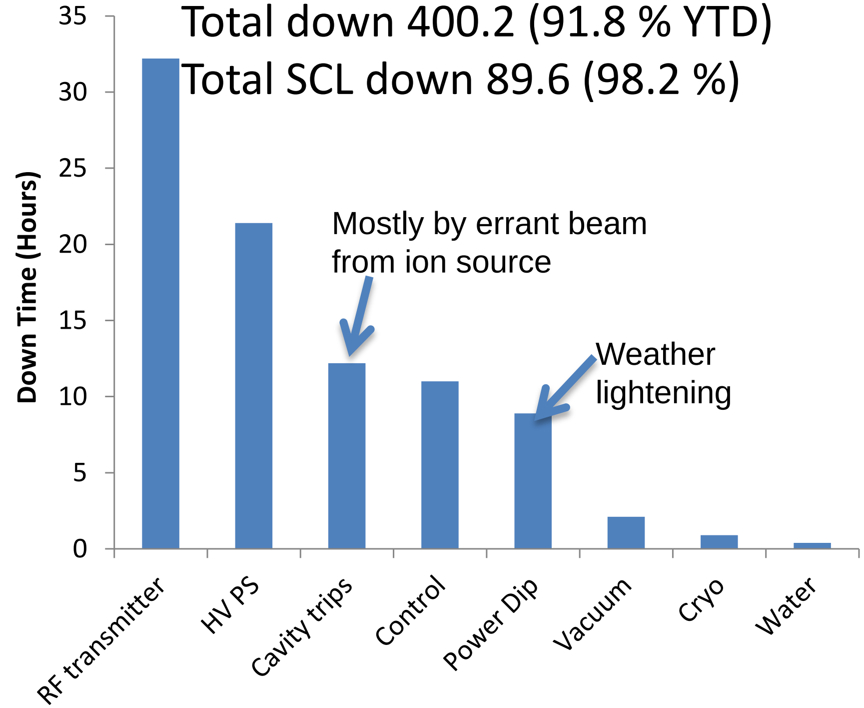


Reliability of high power SCLs

- **The trip rates were one of main concerns for ADS**



Down time statistics of
SNS SCL and related systems
In FY 11 YTD ~200 days of operation
Total Op time 5036 hours
Total down 400.2 (91.8 % YTD)
Total SCL down 89.6 (98.2 %)



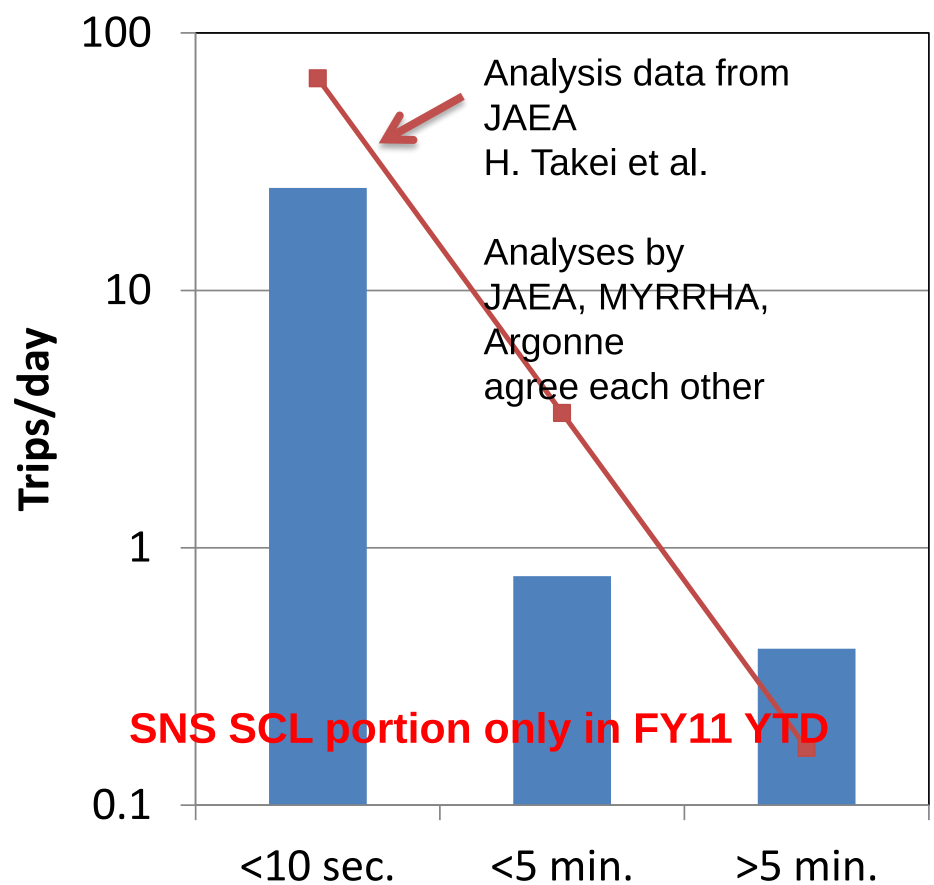
Reliability and trip rate

- In ADS trip rate is very critical ← thermal stress & fatigue on reactor
- SNS data: trips of SCL and SCL supporting systems only (i.e. cavity, RF, HVPS, control, water, vacuum, cryo, weather related…)
- Fast recovery from a cavity trip has been demonstrated at SNS

H. Takei, et. Als, *Estimation of Acceptable Beam Trip Frequencies of Accelerators for ADS and Comparison with Performances of Existing Accelerators, TCADS-1, OECD/NEA, March 2010*

Three criteria depending on the beam trip duration *T*

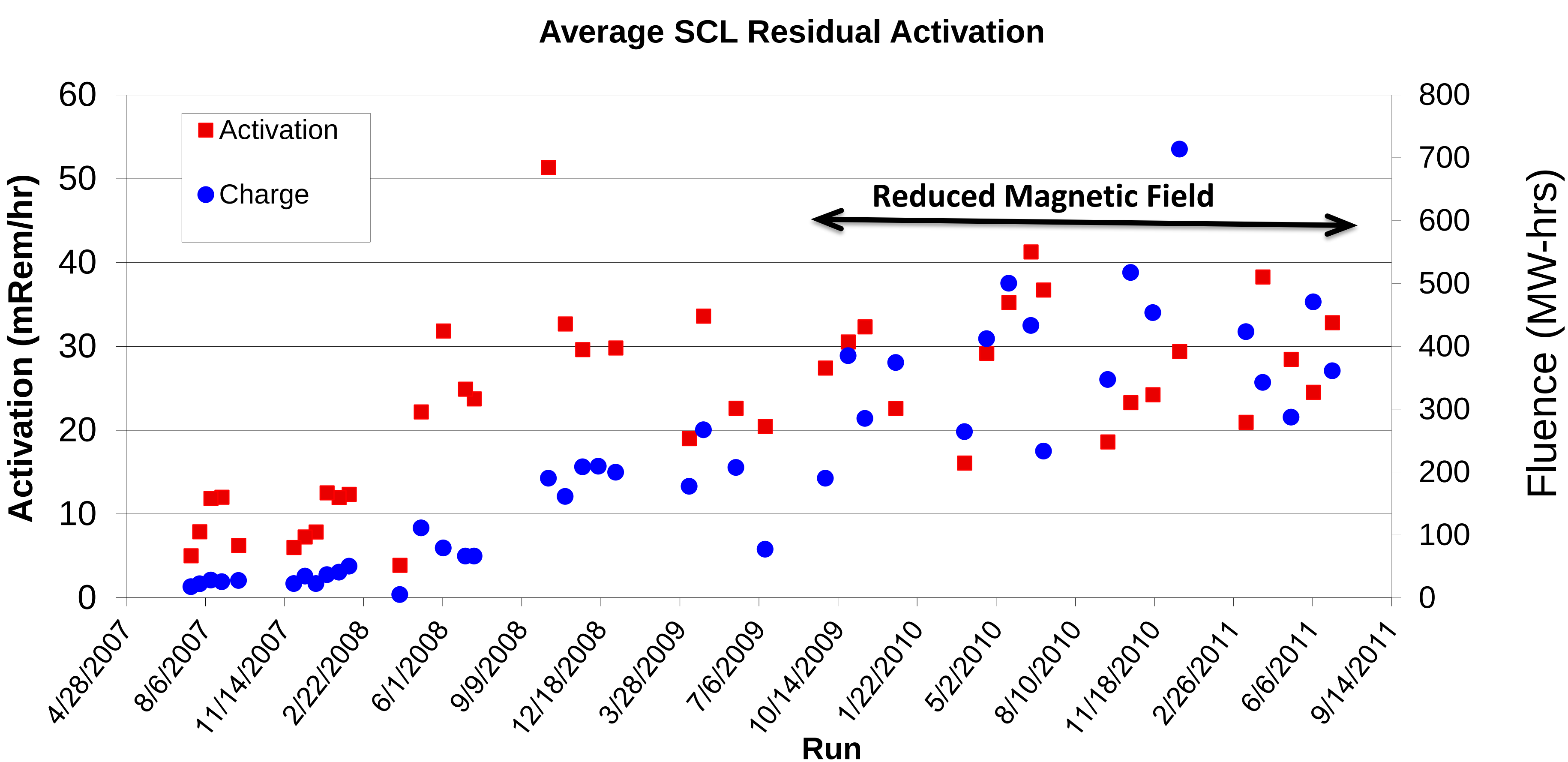
Beam trip duration *T*	Acceptable Frequency	Remarks
0 < T < 10 sec.	$4 \cdot 10^4$ / 2 years > 10^6 / 2 years 10^6 / 40 years (20,000 / y)	Beam window life time Cladding tube life time Fatigue failure of inner barrel
10 sec. < T < 5 min.	$4 \cdot 10^4$ / 40 years (1,000 / y)	Fatigue failure of reactor vessel
T > 5 min.	Once a week (50 /y)	Plant availability



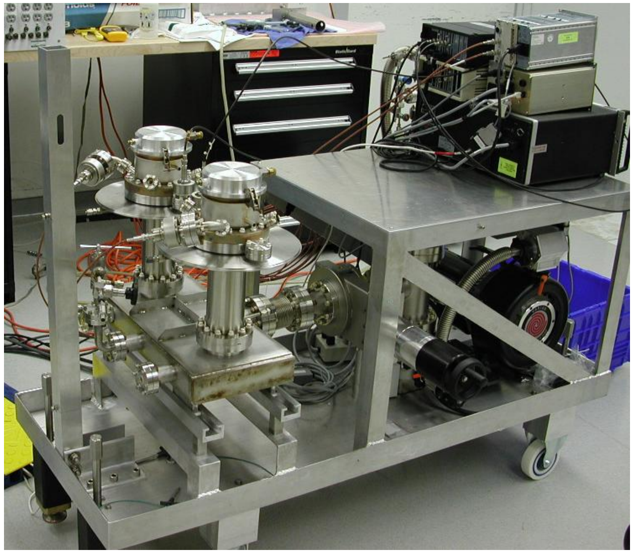
Beam loss/activation in high power SCLs

- <1 W/m uncontrolled loss (ref. 1 GeV proton beam)
- SNS experience: no show stopper roughly up to 10 MW and…
  - H- beam: IBS?
  - More controlled scraping

→ Can go higher

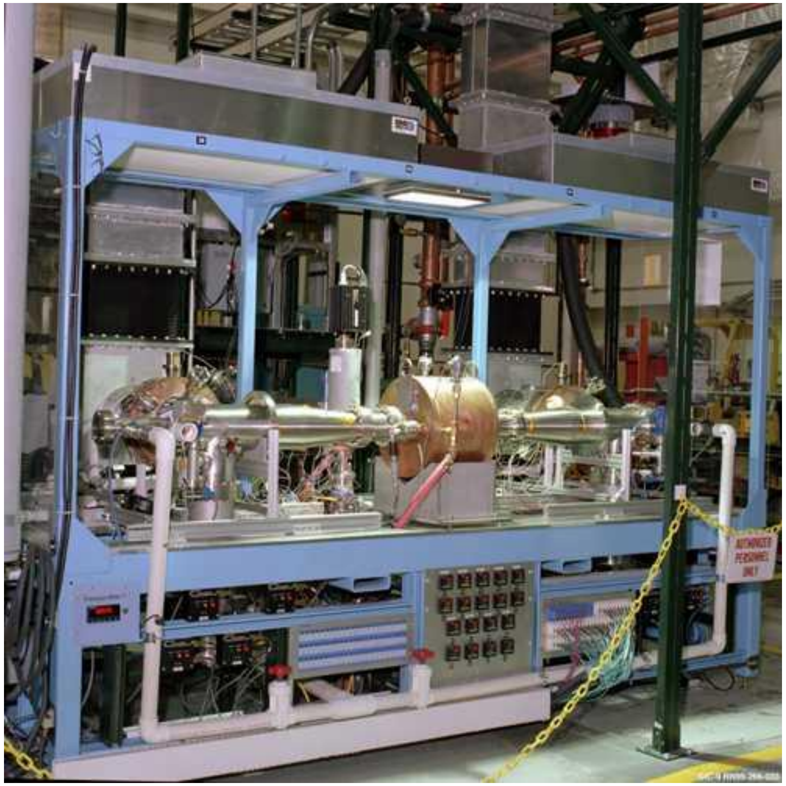


Power Couplers



SNS Test Cart
Tested to 1.2 MW TW pulsed
Pulse operation: 550kW in routine operation (TW+SW)

KEK 508 MHz
~400kW CW in operation



APT Test Stand
1 MW CW operation

Higher-order-mode in high power proton SCLs

- Beam dynamics (transverse, longitudinal)
- HOM power build-up around beam spectral lines
- Wake-field loss $qI_{b0}\sum_{n}\frac{\omega_n}{4}\left(\frac{r}{Q}\right)_n$

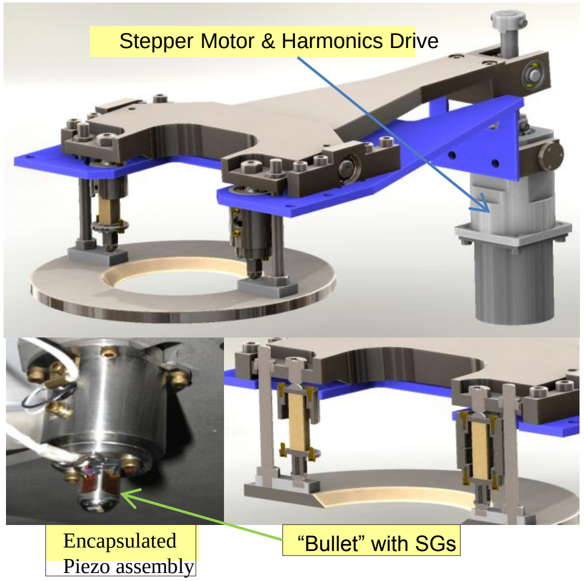
- Lower frequency < 1 GHz
- Less chance for trapped mode (less no. of cells < 6~7, asymmetry)
- Smaller charge/bunch <a few hundreds pC per bunch
- Scattering of HOMs

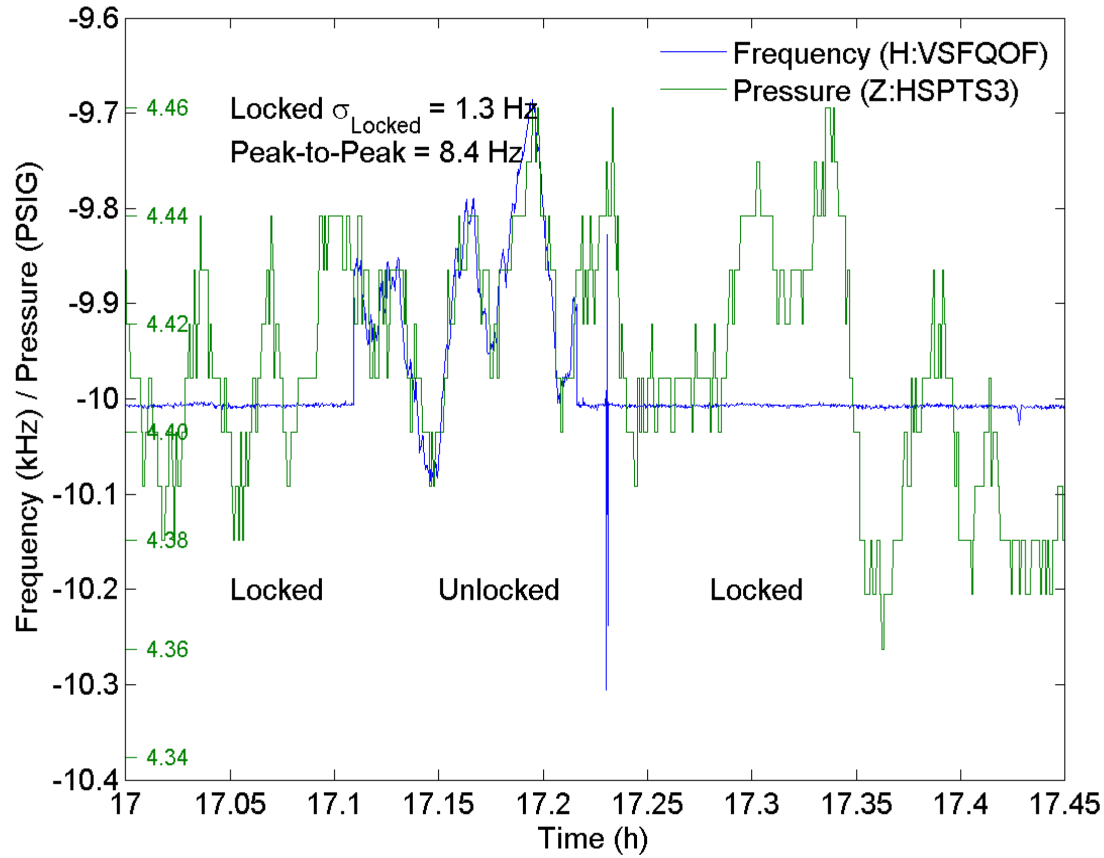
- Careful analyses are required
- HOM couplers may not be needed (SNS, Pr-X, SPL)

Low bandwidth of SRF cavities

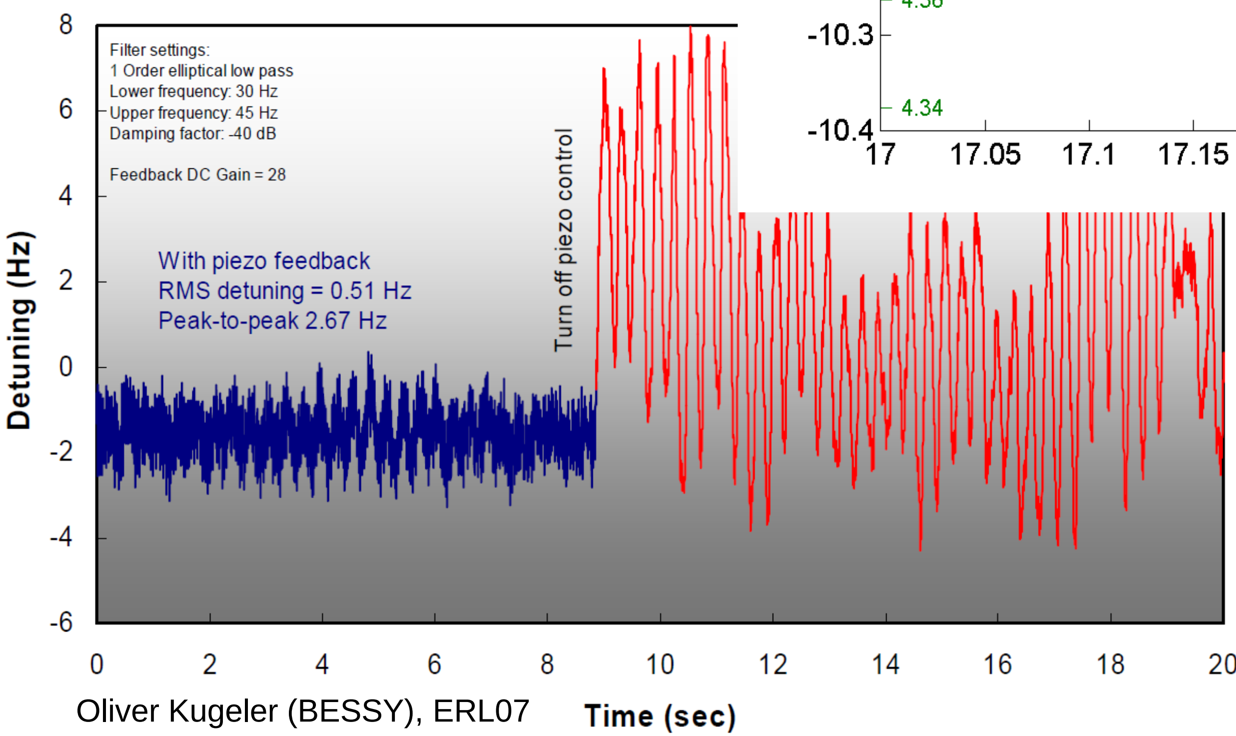
- Especially for small beam loading: < ~ a few mA peak
- Very narrow bandwidth at matched condition (RF efficiency): < 10 Hz
- Active compensation of microphonics
- Characterization of system (transfer functions)
- Very promising results

- Demonstration at operational condition (statistically optimum)
- Reliability of system
- High frequency resonances





Warren Schappert, Yuriy Pischalnikov
(FNAL, Project-X Coll. Meeting 2011)



Oliver Kugeler (BESSY), ERL07

Summary

- **Neutron sources by high power ion accelerators address many of the challenges: science, energy, materials, environment, etc.**
- **SRF became a technology of choice for high power ion beam accelerator: especially for high power and high duty factor machines**