Compact Pulsed Hadron Source

Course N-2

Introduction to SNS Facilities

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CPHS

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Class Outline

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   - 2.2 Primary parameters
   - 2.3 Beam evolution parameters
3. Beam loss & activation
4. Major accelerator systems
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1. Overview

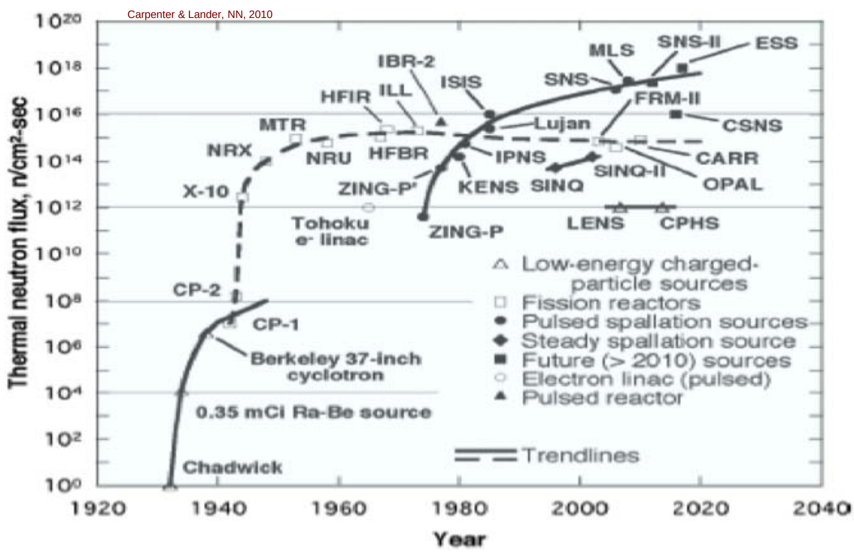
Neutron production mechanisms

Neutron producing mechanisms of significant yield are:

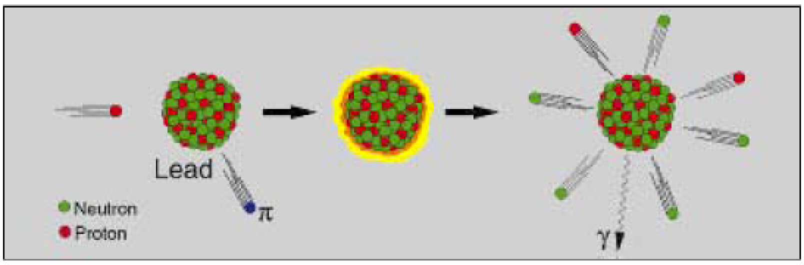
- Charged-particle reactions, e.g., $^{9}Be + p \rightarrow {}^{9}B + n$, $^{2}H + {}^{3}H \rightarrow {}^{3}He + n$
- (α,xn) radioactive isotopes, e.g., $^{226}Ra \rightarrow \alpha$, $\alpha + {}^{9}Be \rightarrow {}^{13}C^* \rightarrow {}^{12}C + n$
- Photoproduction, e.g., $\gamma + {}^{181}Ta \rightarrow {}^{180}Ta + n$, $\gamma + {}^{2}H \rightarrow {}^{1}H + n$
- (n,xn), e.g., $^{9}Be + n \rightarrow {}^{8}B^* + 2n$
- Excited-state decay, e.g., $^{13}C^{**} \rightarrow {}^{12}C^* + n$, $^{130}Sn^{**} \rightarrow {}^{129}Sn^* + n$,
- Fission, e.g., $^{235}U + n \rightarrow A^* + B^* + xn$; $\langle x \rangle \sim 2.5$
- Spallation, e.g., $p + {}^{184}W \rightarrow A^* + B^* + xn$, $\langle x \rangle \sim 20$

- Practical sources for scattering science
  - Fission (reactor-based sources)
  - Spallation (large accelerator-based sources)
  - Charged-particle reaction (compact sources)

History of neutron source developments



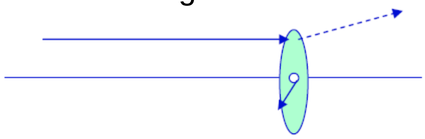
What is spallation neutron source?



- High energy (~GeV) protons hit a heavy-metal target
- A proton “heats-up” the entire metal atom
- Energy released “evaporates” spallation neutrons
- 1 proton → 20 ~ 30 neutrons (high flux)
- Moderated to energies suitable for experiments
- 5 MW SNS ~ 60MW high-flux reactor ~ $1x10^{15}n/cm^2s$ average neutron flux
- Number of neutron ~ proton energy (0.2 ~ 10 GeV)

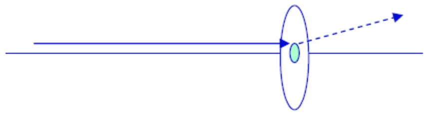
Radiation scattering methods comparison

Electron, X-ray, laser scattering

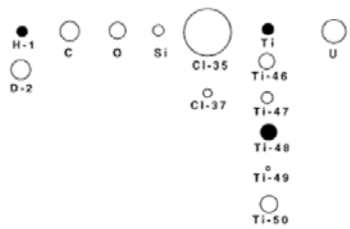


- Interaction is electromagnetic
- Scattering length ~ 10^{-10} m
- Penetration depth ~ 10^{-6} m
- Not sensitive to isotopes

Neutron scattering



- Interaction is neutron-nuclear
- Scattering length ~ 10^{-15} m
- Penetration depth ~ 10^{-2} m
- Sensitive to isotopes 对氢、碳、氮等敏感（生物、脂肪、石油、爆炸物）

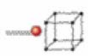


Neutron – a tailor-made probe

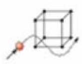
Neutrons are NEUTRAL particles. They
- are highly penetrating,
- can be used as nondestructive probes, and
- can be used to study samples in severe environments.

Neutrons have a MAGNETIC moment. They can be used to
- study microscopic magnetic structure,
- study magnetic fluctuations, and
- develop magnetic materials.

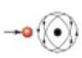
Neutrons have SPIN. They can be
- formed into polarized neutron beams,
- used to study nuclear (atomic) orientation, and
- used for coherent and incoherent scattering.



The ENERGIES of thermal neutrons are similar to the energies of elementary excitations in solids. Both have similar
- molecular vibrations,
- lattice modes, and
- dynamics of atomic motion.



The WAVELENGTHS of neutrons are similar to atomic spacings. They can determine
- structural sensitivity,
- structural information from 10^{-13} to 10^{-4} cm, and
- crystal structures and atomic spacings.



Neutrons "see" NUCLEI. They
- are sensitive to light atoms,
- can exploit isotopic substitution, and
- can use contrast variation to differentiate complex molecular structures.

- What do we need? More flux!

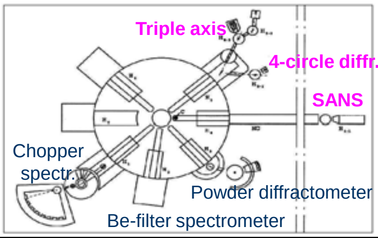
Types of high power accelerators

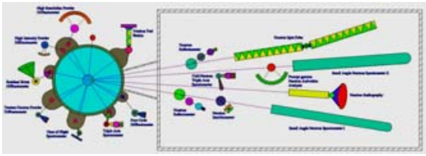
- CW facilities
  - Driven by a high intensity proton cyclotron
  - 1.2 MW SINQ (PSI) driven by 590 MeV cyclotron
- Long (ms) pulse facilities
  - Driven by a high intensity proton linac
  - 1 MW LANSCE (LANL) driven by 800 MeV linac
  - (5 MW design) ESS (Lund) driven by 2.5 GeV linac
- Short (μs) pulse facilities
  - Driven by a combination of linacs and rings
  - Partial energy linac and rapid-cycling synchrotron(s):
    - *ISIS (RAL) driven by 70 MeV linac/800 MeV RCS*
    - *J-PARC driven by 400 MeV linac/3 GeV RCS/50 GeV MR*
  - Full-energy linac and an accumulator ring:
    - *PSR (LANL) driven by 800 MeV linac/accumulator*
    - *1 MW SNS (ORNL) driven by 1 GeV linac/accumulator*

1.1 Continuous-wave sources

中国先进研究堆 CARR（替代HWRR）

60 MW, thermal flux of 8×10^{14} n/cm^2•sec



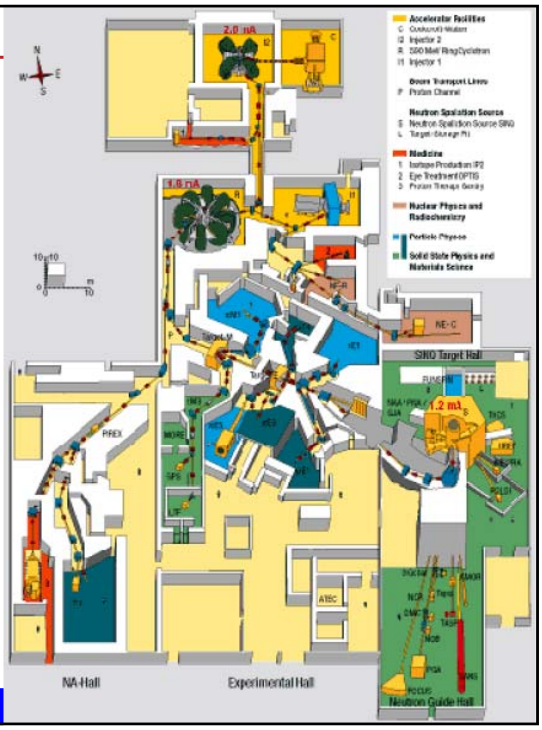


Guide hall housing cold-neutron instruments

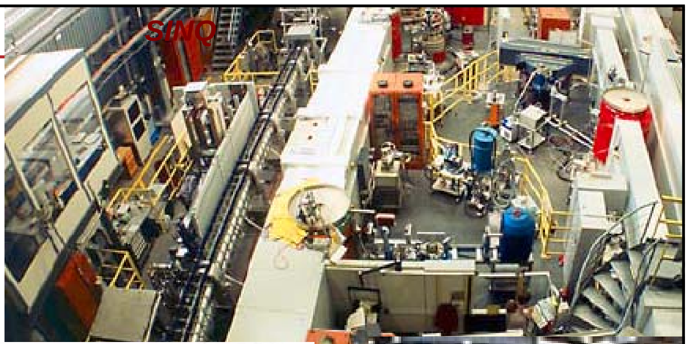
Reactor hall using thermal neutrons

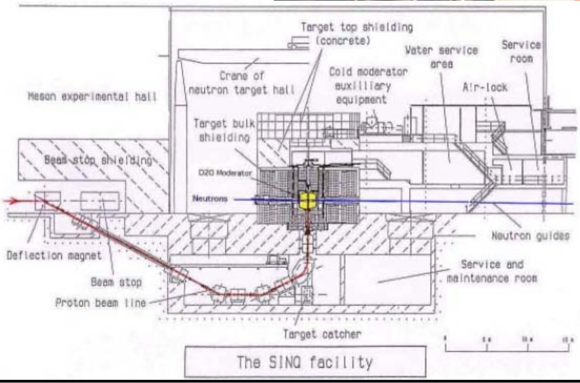
SINQ, PSI

- Cockcroft-Walton, injector cyclotron, 590 MeV cyclotron
- 1 MW cw proton beam



SINQ





1.2 Long-pulse sources

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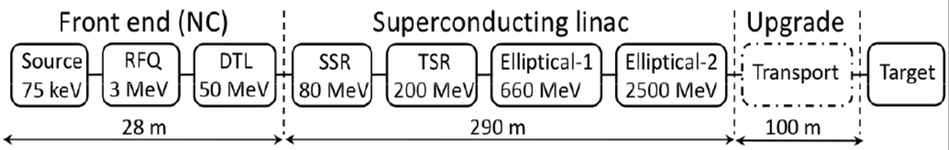
ESS (Lund)

- Earlier short-pulse ESS (1.33 MeV linac, double AR, 5 MW) delayed & stopped
- New ESS focuses on long pulse applications to complement SNS, JSPS, and ISIS

ESS parameters



System	T [K]	Energy [MeV]	Freq. [MHz]	β v/c	Length [m]
Source	300	0.075	–	–	2.5
LEBT	300	–	–	–	1.1
RFQ	300	3	352.2	–	4.0
MEBT	300	–	352.2	–	1.1
DTL	300	50	352.2	–	19.2
SSR	4	80	352.2	0.35	23.3
TSR	4	200	352.2	0.50	48.8
Ellipt-1	2	660	704.4	0.65	61.7
Ellipt-2	2	2500	704.4	0.92	154.0

1.3 Short-pulse sources

英国RAL 中子谬子源 ISIS 和光源 DIAMOND

英国中子谬子源靶站大厅

- 装置价值约28亿元
- 年运行经费约4亿元
- 运行人员300人
- 每年约700个实验
- 每年约1700名用户
- 束流功率160千瓦
- 验收后约10年达到设计功率指标
- 已成功运行20余年。最近升级其质子加速器和建设第二靶站。

CPNS Courtesy RAL 19

日本质子加速器研究中心 J-PARC

- JAEA和KEK合作，预研15年建设8年，耗资一期1527亿日元，350工程人员，将于2009年建成
- 建材料生命（即中子谬子源）、中微子、高能强子装置；二期363亿日元，拟建ADS验证装置等

(Courtesy J-PARC)

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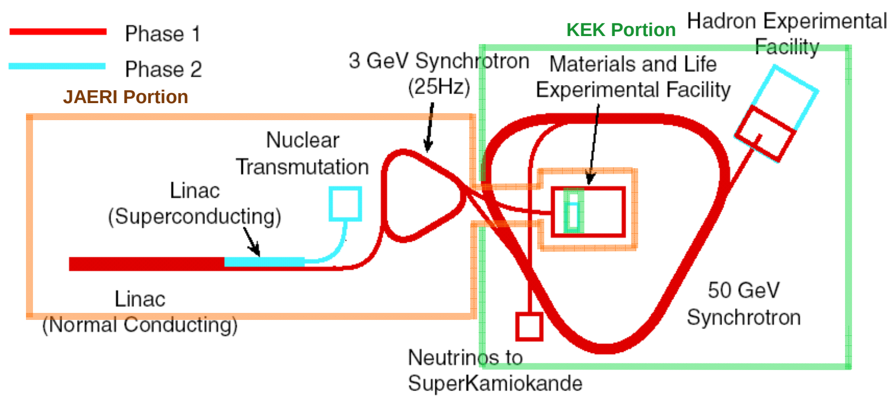
J-PARC in phases



– Phase 1 + Phase 2 = 1,890 Oku Yen (= $1.89 billions if $1 = 100 Yen).
  – Phase 1 = 1,527 Oku Yen (= $1.5 billions) for 7 years.
 – JAERI: 860 Oku Yen (56%), KEK: 667 Oku Yen (44%).

美国散裂中子源 Spallation Neutron Source

- 6所美国国家实验室合作，预研3年建造7年，耗资14亿美元（含人员），建设峰期780人，于2006年建成，目前世界最强中子源
- 在建SNS同时，邻建纳米材料中心及超级计算中心

SNS budget (2004)

WBS	May 2004 Review EAC ($M)		Nov 2004 Review EAC ($M)	
1.02 Project Support	75.1		72.7	
1.03 Front End Systems	20.8		20.8	
1.04 Linac Systems	316.8		314.0	
1.05 Ring & Transfer System	142.4		144.0	
1.06 Target Systems	109.0		111.5	
1.07 Instrument Systems	63.5		63.8	
1.08 Conventional Facilities	379.9		388.3	
1.09 Integrated Control Systems	59.8		59.8	
EAC	1,167.4		1,174.9	
Contingency $	**25.3**	**20.8%**	**17.8**	**20.1%***
TEC	1,192.7		1,192.7	
R&D	100.0		100.0	
Pre-Ops	119.0		119.0	
OPC	219.0		219.0	
TPC	1,411.7		1,411.7	

* Based on EAC and actual costs and awards through September 30, 2004

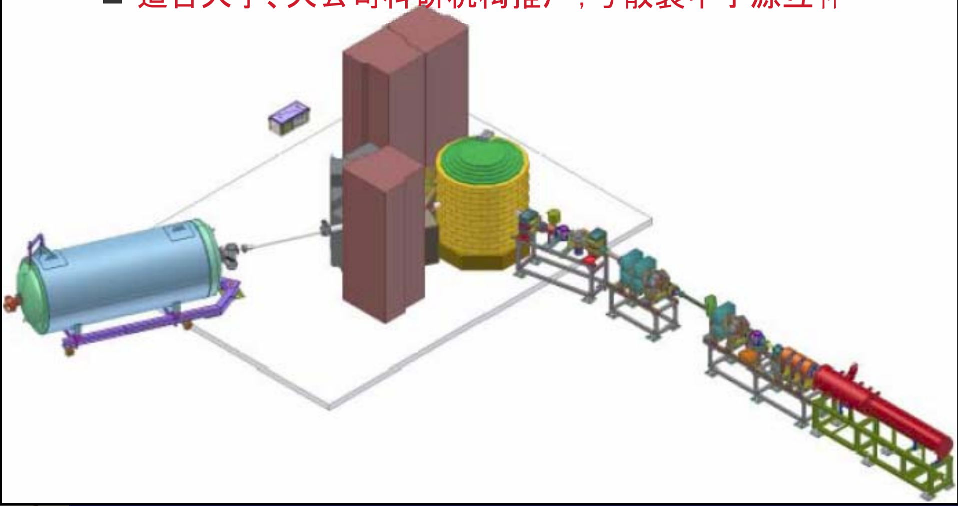
中国散裂中子源 CSNS

建设场地广东东莞大朗 · 松山湖

1.4 Compact sources

美国LENS 微型脉冲源

- 美国 Indiana Univ.的 Low Energy Neutron Source
- 侧重冷源，2004年底初调通；准备逐步升级加速器，增加束流能量及强度
- 适合大学、大公司科研机构推广；与散裂中子源互补



Tsinghua University Compact Pulsed Hadron Source

Table 1: Primary parameters of CPHS

Proton power on target	16	kW
Proton energy	13	MeV
Average beam current	1.25	mA
Pulse repetition rate	50	Hz
Protons per pulse	$1.56x10^{14}$	Protons
Pulse length	0.5	ms
Peak beam current	50	mA
Target material	Be	
Moderator type	H_2O (300K), CH_4 (20K)	

- Cost at $12M (w/o labor); funded $3M
- 3 year for phase I

- ECR source
- RFQ
- DTL
- RF(325 MHz)
- Be target
- SANS
- Imaging
- Irradiation

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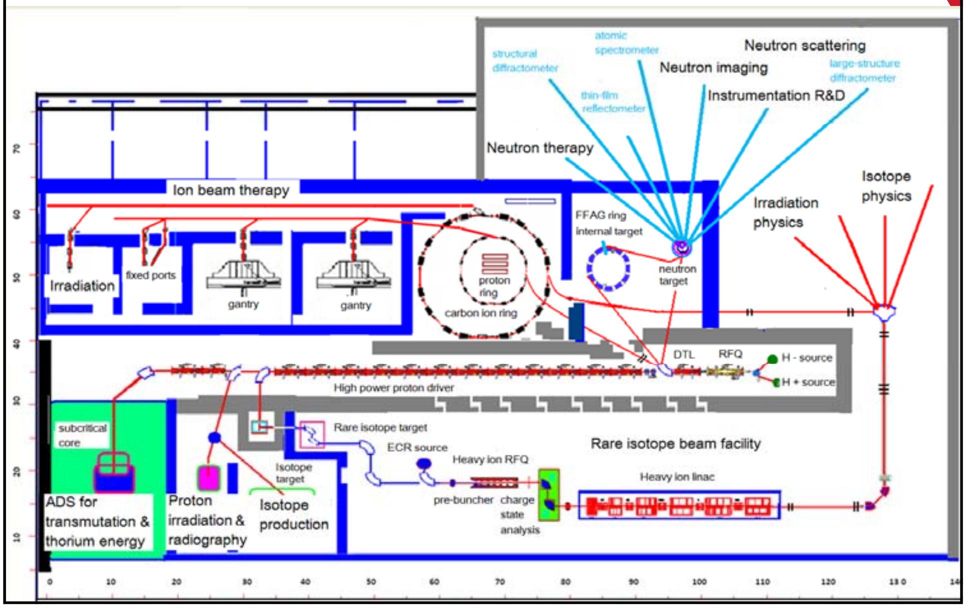
A possible layout of 10,000 m² building



2. Beam characteristics

Beam characteristics

- Beam time structure
- Primary parameters
  - Ion species; Kinetic energy
  - Repetition rate
  - Pulse intensity; Bunch length
  - Emittances
- Beam evolution parameters

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Major SNS parameters

Proton beam power on target	1.4	MW
Proton beam kinetic energy on target	1.0	GeV
Average beam current on target	1.4	mA
Pulse repetition rate	60	Hz
Protons per pulse on target	1.5×10^{14}	protons
Charge per pulse on target	24	μC
Energy per pulse on target	24	kJ
Proton pulse length on target	695	ns
Ion type (Front end, Linac, HEBT)	H minus	
Average linac macropulse H- current	26	mA
Linac beam macropulse duty factor	6	%
Front end length	7.5	m
Linac length	331	m
HEBT length	170	m
Ring circumference	248	m
RTBT length	150	m
Ion type (Ring, RTBT, Target)	proton	
Ring filling time	1.0	ms
Ring revolution frequency	1.058	MHz
Number of injected turns	1060	
Ring filling fraction	68	%
Ring extraction beam gap	250	ns
Maximum uncontrolled beam loss	1	W/m
Target material	Hg	
Number of ambient / cold moderators	1/3	
Number of neutron beam shutters	18	
Initial number of instruments	5	

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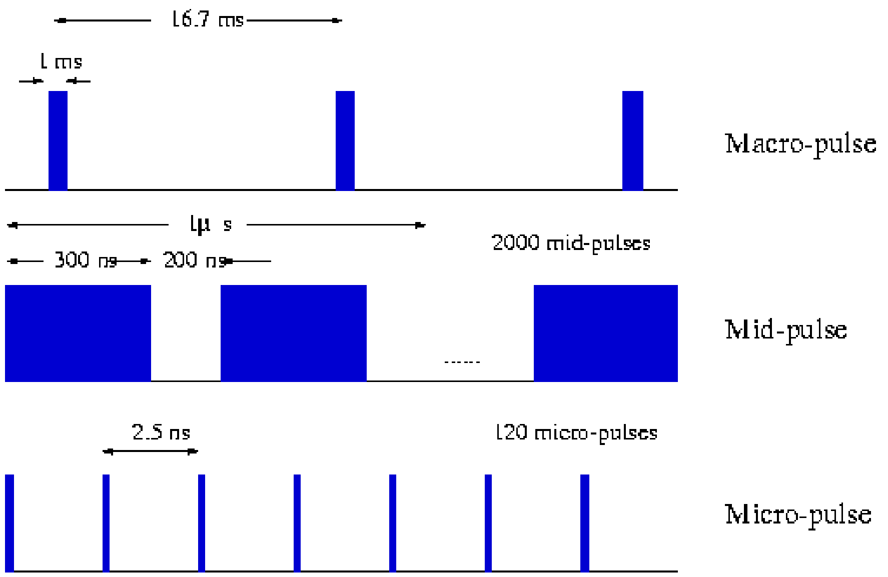
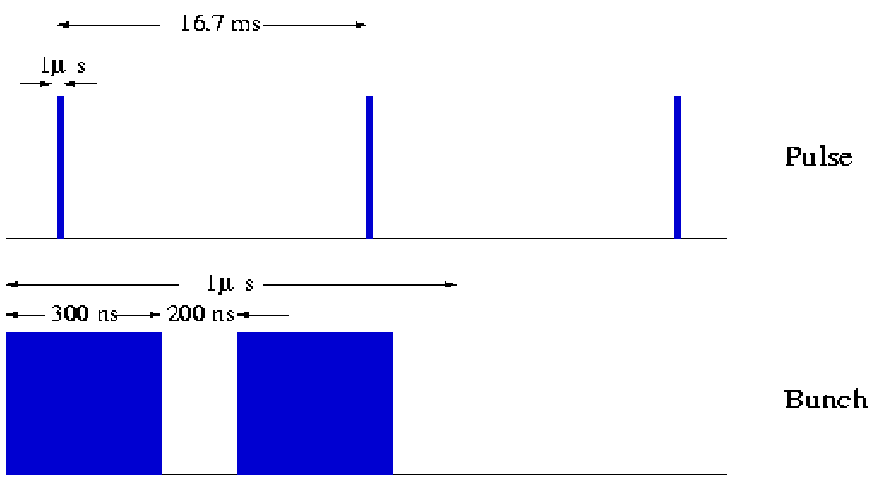
Time structure (linac)



Time structure (ring)



Beam power

- Characterizing the "power" of a high-intensity accelerator

  $\langle P \rangle = E_k \langle I \rangle$ energy & average current

- Average current of "facility"

  $$\langle I \rangle = f_N N_p e$$

  - Repetition rate
  - Number of particles per pulse
- Raise energy, increase repetition rate, increase pulse intensity

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Ion species

- H^- ion is used for short pulse applications
  - Allows multi-turn accumulation to enhance pulse intensity
  - Controls beam profile
  - Demands a powerful H^- ion source
  - Complication with electron stripping under gas scattering and under magnetic field
    - *Gas scattering: requiring relatively high vacuum*
    - *Magnetic stripping: limits maximum magnetic field*
    - *Black-body stripping: significant above 5 GeV*
- Proton beam is usually used for high-intensity cw or long pulse applications in the absence of rings

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Kinetic energy

- Range largely determined by applications & experiments
  - E.g. 0.5 – 5 GeV for neutron spallation
- Within a given range, a higher output energy implies
  - a higher output beam power, relatively “cheap” to achieve for a RCS (linearly proportional)
  - alleviated heating on target due to longer stopping length
  - higher magnet field, higher ramping power, more difficult field quality control
- A higher injection energy implies
  - reduced space-charge effects due to electro-magnetic force cancellation
  - more probably magnetic stripping demanding lower field, longer magnet, more injection space
  - higher cost of the injector accelerator

Repetition rate

- Requirements from the user / target: 10 – 60 Hz
  - Time resolution & power per pulse needs -> lower rate
  - Total beam power, easier target tolerance -> higher rate
- Rapid-Cycling Synchrotrons: sensitive to repetition rate
  - Demands a strong power supply
  - Demands a high radio-frequency (RF) voltage
  - Demands RF shielding to avoid heating on vacuum chamber while allowing image charge to circulate (impedance control)
  - Demands lamination to avoid heating in magnets
- Accumulators: less sensitive comparing with RCS
  - More demanding on the pre-injector (ion source output, linac klystron power …)
  - Higher injection energy, lower extraction energy
  - Higher ring intensity (instabilities) and beam loading

Pulse intensity

- Proportional to output beam power – as high as possible
- Usually limited by space charge constraints, instability threshold, instability growth
- Ring average current $\bar{I} = Nef_s$
- Ring peak current $\hat{I}$

  parabolic: $\hat{I} = \frac{3\pi}{2\hat{\phi}}\bar{I}$ Gaussian: $\hat{I} = \frac{1}{\sqrt{2\pi}\sigma_\phi}\bar{I}$
- Bunching factor $B = \bar{I}/\hat{I} \le 1$

  parabolic: $B = \frac{C - L_{gap}}{C}\frac{2}{3}$ Gaussian: $B \approx \frac{\sqrt{2\pi}}{6} \approx 0.42$

  Empirically: ~0.5 (accumulator); ~0.35 (RCS)

Bunch length

- Range largely determined by applications & experiments
  - E.g. ~ 1 ns for neutrino factory proton drivers
  - Spallation neutron: not sensitive to bunch length
- Choice of Radio Frequency accelerating system
  - Hardware availability considering wide RF frequency sweep
  - Consideration of possible coupled-bunch instability
  - Needs for a clean beam gap for extraction
    - *For low harmonic: control bunch area/bucket area ratio*
    - *For high harmonic: missing bunches*

Emittances

- Transverse emittance

  constant of acceleration: $\oint x dp_x \qquad p_x \sim \beta\gamma x'$

  – Preservation of normalized emittance often needed for downstream applications; damping is not practical

  – Controlled emittance enlargement is used to alleviate space-charge effects & target stress; constraints from magnet aperture and power supply

- Longitudinal emittance

  constant of acceleration:

$$\oint \phi dW \qquad W \equiv \frac{\Delta E}{h\omega_s}; \qquad \frac{\Delta E}{E} = \beta^2 \frac{\Delta p}{p}$$

  – Needed momentum spread to damp possible instabilities

  – Often limited by the available momentum acceptance

SNS beam evolution parameters

	Front End			Linac					Ring		
	IS/LEBT	RFQ	MEBT	DTL	CCL	SCL (1)	SCL (2)	HEBT	Ring	RTBT	Unit
Output Energy	0.065	2.5	2.5	86.8	185.6	391.4	1000	1000	1000	1000	MeV
Relativistic factor β	0.0118	0.0728	0.0728	0.4026	0.5503	0.7084	0.875	0.875	0.875	0.875	
Relativistic factor γ	1.00007	1.0027	1.0027	1.0924	1.1977	1.4167	2.066	2.066	2.066	2.066	
Peak current	47	38	38	38	38	38	38	38	9×10^4	9×10^4	mA
Minimum horizontal acceptance			250	38	19	57	50	26	480	480	πmm mr
Output H emittance (unnorm., rms)	17	2.9	3.7	0.75	0.59	0.41	0.23	0.26	24	24	πmm mr
Minimum vertical acceptance			51	42	18	55	39	26	480	400	πmm mr
Output V emittance (unnorm., rms)	17	2.9	3.7	0.75	0.59	0.41	0.23	0.26	24	24	πmm mr
Minimum longitudinal acceptance			4.7E-05	2.4E-05	7.4E-05	7.2E-05	1.8E-04		19/π		πeVs
Output longitudinal rms emittance		7.6E-07	1.0E-06	1.2E-06	1.4E-06	1.7E-06	2.3E-06		2/π		πeVs
Controlled beam loss; expected	0.05[a]	N/A	0.2[b]	N/A	N/A	N/A	N/A	5[c]	62[d]	58[e]	kW
uncontrolled beam loss; expected	70	100[f]	2	1	1	0.2	0.2	<1	1	<1	W/m
Output H emittance (norm., rms)	0.2	0.21	0.27	0.33	0.39	0.41	0.41	0.46	44	44	πmm mr
Output V emittance (norm., rms)	0.2	0.21	0.27	0.33	0.39	0.41	0.41	0.46	44	44	πmm mr

Note a) corresponding to 27% chopped beam
b) corresponding to 5% chopped beam
c) beam loss on the transverse and momentum collimators
d) including total 4% of beam escaping foil and 0.2% beam loss on collimators
e) including 4% beam scattered on the target window
f) corresponding to 20% beam loss averaged over RFQ length

3. Beam loss & activation

Significance of exposure to radiation

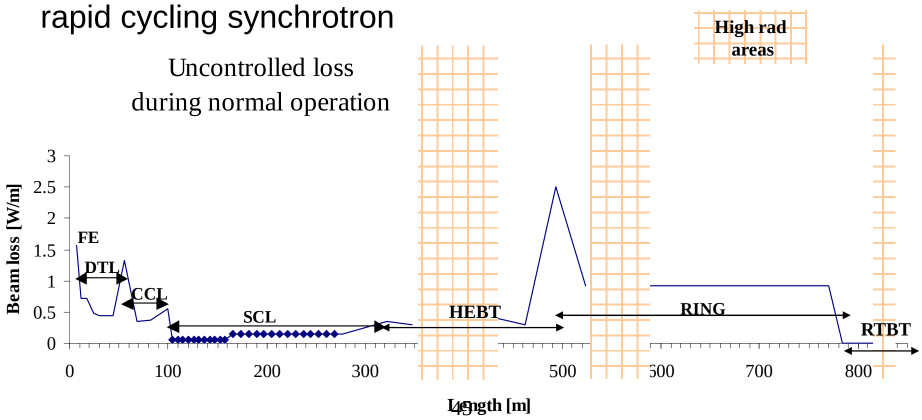
- US occupational limit 50 mSv per year
- DOE laboratory guideline 12.5 mSv per year
- Hands-on maintenance:
  - 1 mSv/hour
  - 50 hours of work per year

(1 Sv = 100 Rem)

Exposure	Significance
3.5 Sv	50% chance of survival
$>$ Sv	Serious to lethal
$>$ 50 mSv	Requiring medical checks
50 mSv.y^{-1}	Occupational dose limit
15 – 50 mSv.y^{-1}	Strict dose control necessary
5 - 15 mSv.y^{-1}	Professional exposure
$<$ 5 mSv.y^{-1}	Minimum control necessary
1 mSv.y^{-1}	Natural background
10 μSv.y^{-1}	Insignificant

Radio-activation & beam loss

- Hands-on maintenance: no more than 1 mSv/hour residual activation (4 h cool down, 30 cm from surface)
- ~ 1 Watt/m uncontrolled beam loss
- ~ 10^{-6} beam loss per tunnel meter at 1 MW operation
- < 10^{-4} beam loss in a 200 m accumulator; ~ 10^{-3} in a 200 m rapid cycling synchrotron



Source of beam loss

- High radio-activation at injection, extraction,collection
  - AGS: up to 100 mSv/hour at localized area
- High beam loss
  - FNAL Booster (25 - 40%): ramp tracking, debunching-recapturing, transition, aperture!
  - AGS/Booster (20 – 30%): pushing record intensity
  - ISIS (~15%): injection capture, initial ramp
  - PSR (0.3% Full energy accumulation): injection loss
  - SNS (~ 10^{-4} Full energy accumulation): average uncontrolled loss

(1) space-charge tune shift (0.25 or larger) & resonance crossing
(2) limited geometric/momentum acceptance
(3) premature H- and H0 stripping and injection-foil scattering
(4) errors in magnetic field and alignment (saturation, fringe, ramp …)
(5) instabilities (resistive wall, electron-cloud instability …)
(6) accidental beam loss (e.g., malfunction of the ion source/linac & misfiring of ring extraction kickers)
(7) beam-halo loss during fast extraction.

Collimation considerations

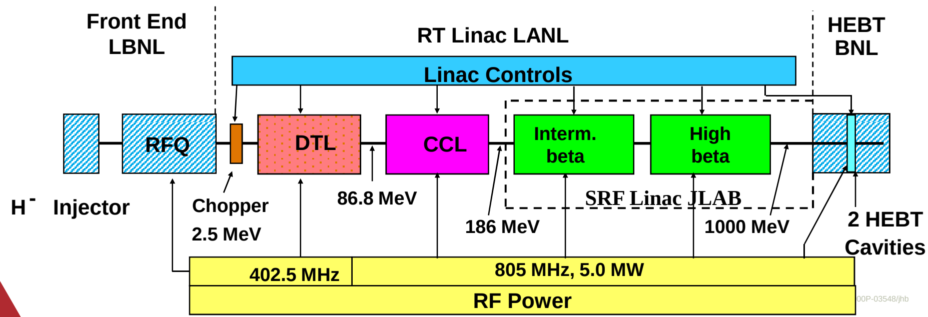
- Multi-step beam gap cleaning
  - LEBT chopping (25 ns)
  - MEBT chopping (10 ns)
  - Ring BIG cleaning
- Multi-step scraping & collimation
  - MEBT, HEBT, Ring, RTBT
- Phase space collimation in transport line
- Two-stage collimation in ring

4. Major accelerator systems

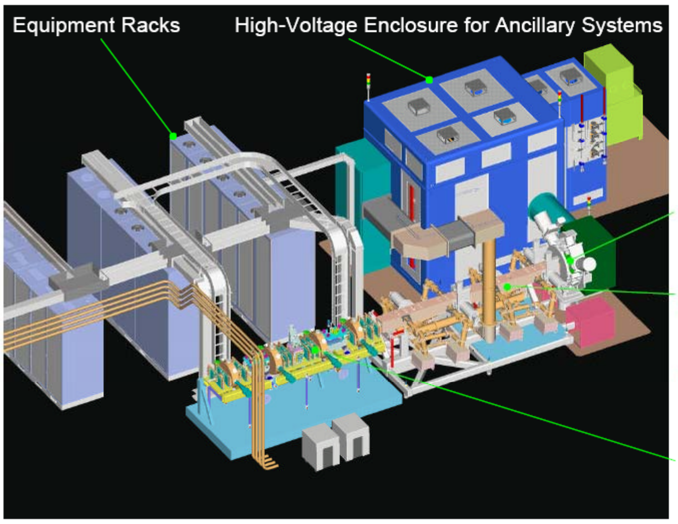
SNS accelerator complex

Linac structure (SNS example)

- Ion source
- Low energy beam transport (LEBT)
- Radio-frequency quadrupole linac (RFQ)
- Medium energy beam transport (MEBT)
- Drift tube linac (DTL)
- Coupled cavity linac (CCL)
- Superconducting RF linac (SCL)



Front end



Ion Source/LEBT
Create 50-mA H^- ion beam

RFQ
Accelerate beam to 2.5 MeV

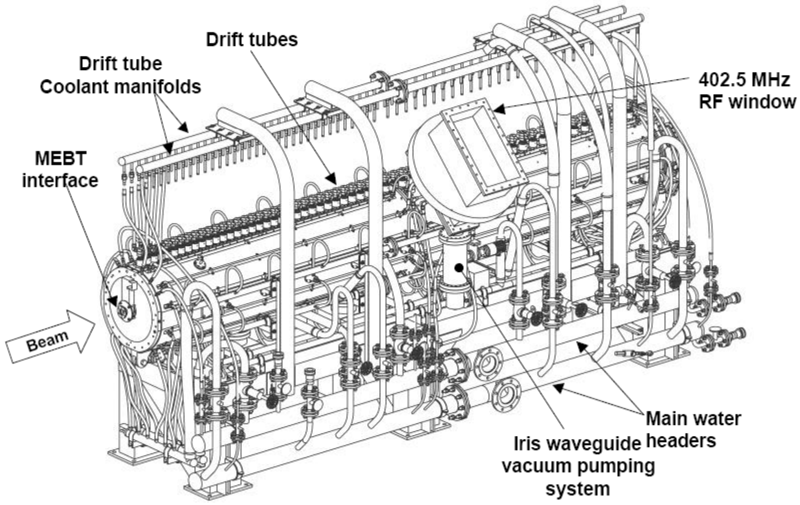
LEBT/ MEBT
Chop beam into mini-pulses

MEBT
Match 40-mA beam into DTL

Front end functions

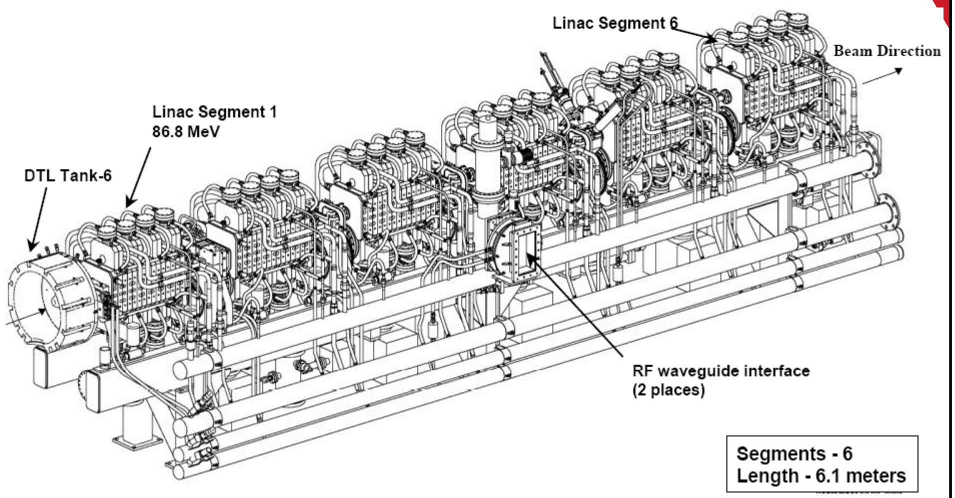
- Ion source
  - High current, low emittance, adequate duty (pulse length) and flatness, long lifetime
- LEBT
  - e- collection, matching, pre-chopping, acceleration
- RFQ
  - Bunching, focusing, acceleration
- MEBT
  - Matching (maintain bunching), chopping, scraping, (optional anti-chopping)

DTL


Drift tubes
Drift tube
Coolant manifolds
402.5 MHz
RF window
MEBT
interface
Beam
Main water
headers
Iris waveguide
vacuum pumping
system

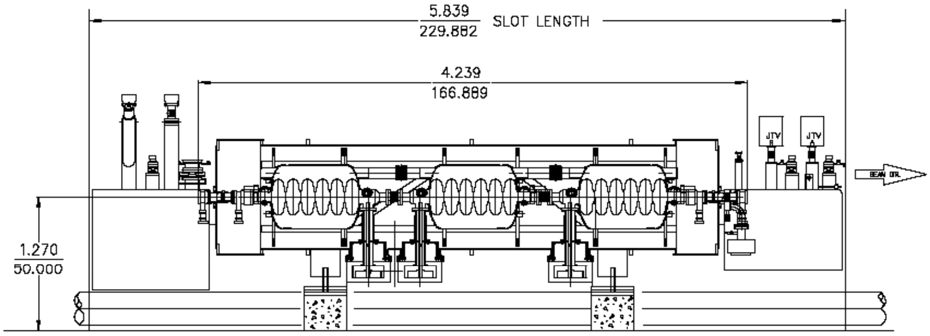
53

CCL

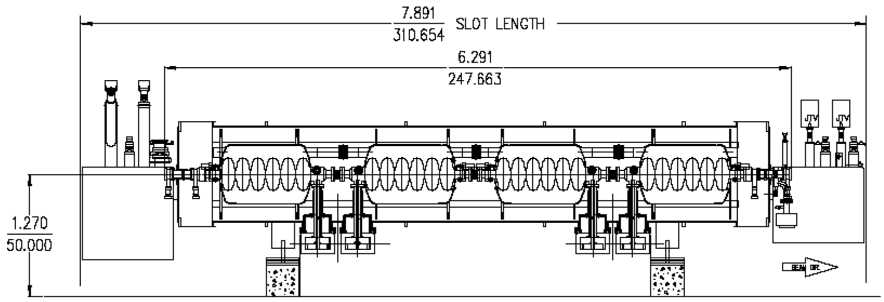

Linac Segment 6
Beam Direction
Linac Segment 1
86.8 MeV
DTL Tank-6
RF waveguide interface
(2 places)
Segments - 6
Length - 6.1 meters

54

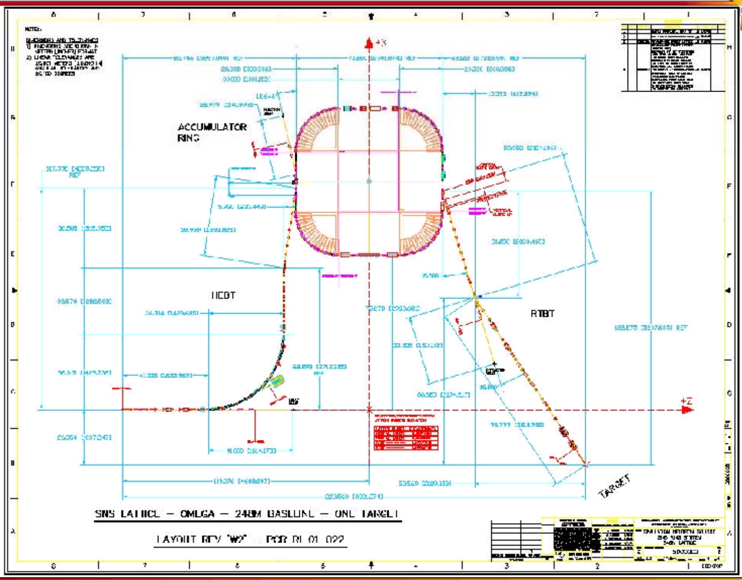
SCL (β=0.61)



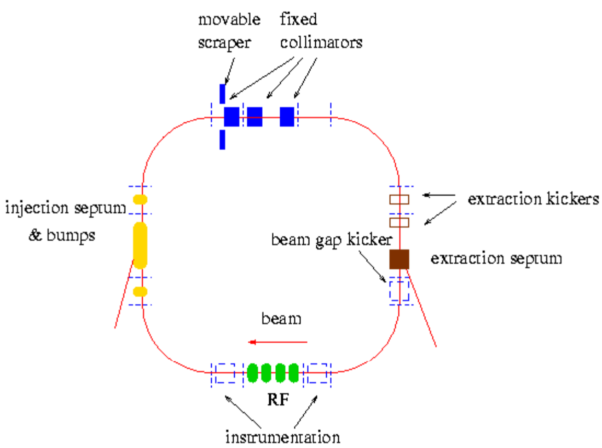
SCL (β=0.81)



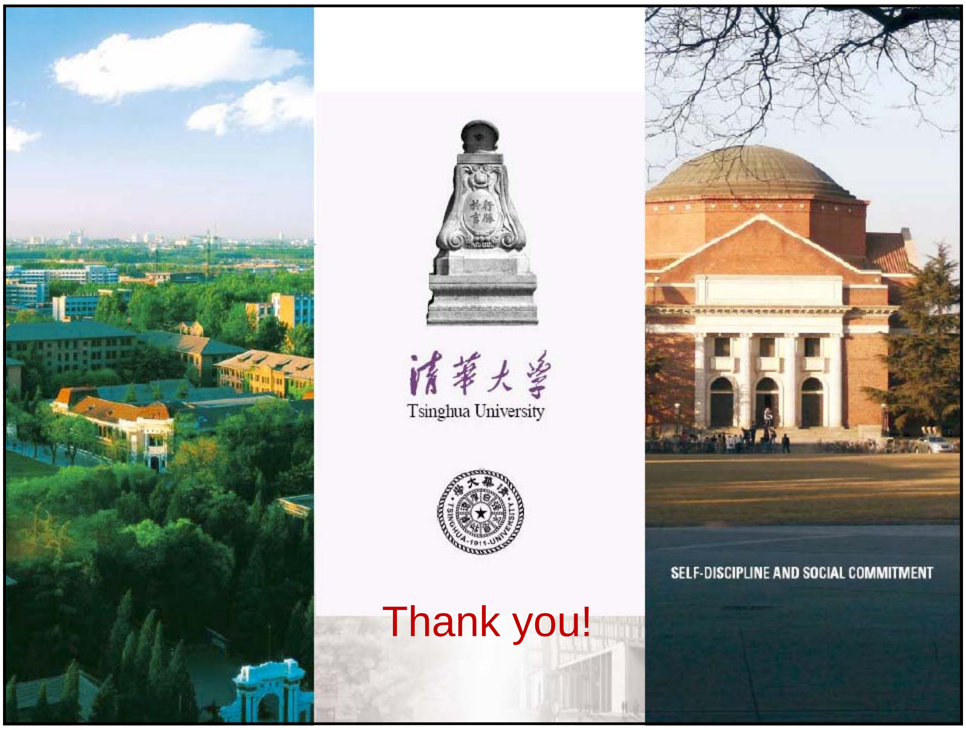
Layout (Frozen Since Aug. 2000)



SNS Ring layout example



- No energy ramping
- Long straight-section, large aperture
  - Injection flexibility
  - Collimation efficiency
- Four straight-sections for four functions
  - Injection;
  - RF;
  - Collimation;
  - Extraction
  - Diagnostics all-around
- Dispersion-free injection
  - Decoupled H, V, L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Thank you!