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Beam physics and technology challenge for multi-MW CW superconducting proton linac for ADS

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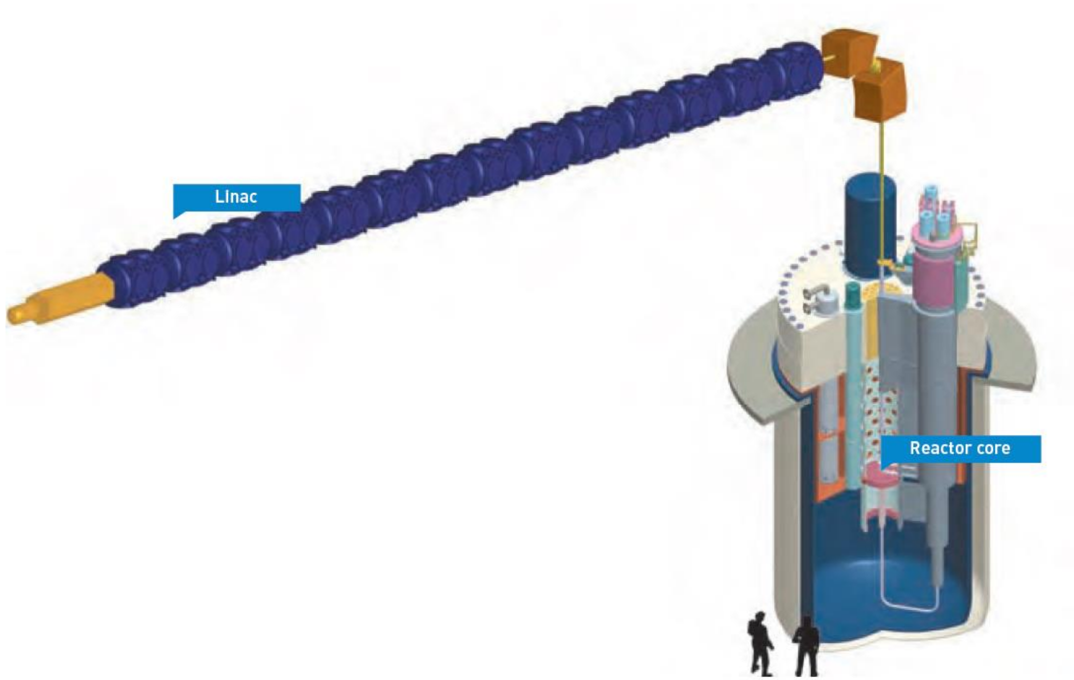
Institute of Modern Physics, CAS

Outlines

- General consideration and requirements of an accelerator for ADS
- Overview and challenge of Multi-MW sc-linacs
- The challenge of beam physics and the considerations during design of C-ADS
- The challenge of technology and some experiences of SARAF and C-ADS
- References and Acknowledgement

Accelerator Driven Systems



S. Henderson, FNAL Colloquium Feb. 15, 2012

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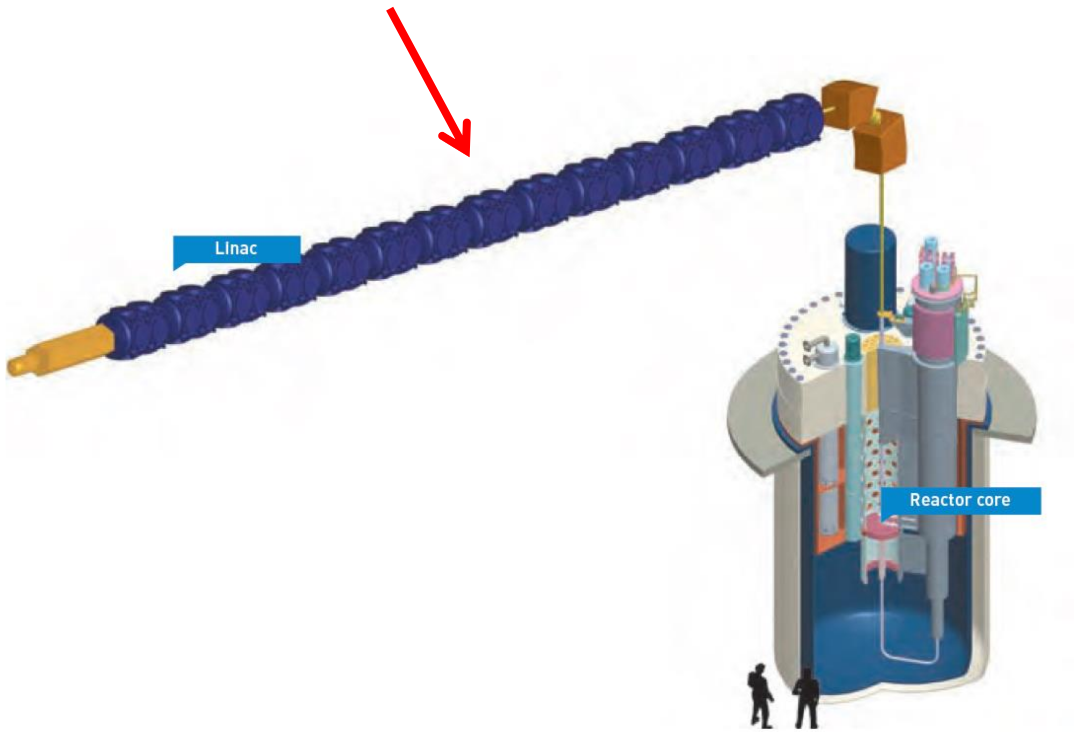

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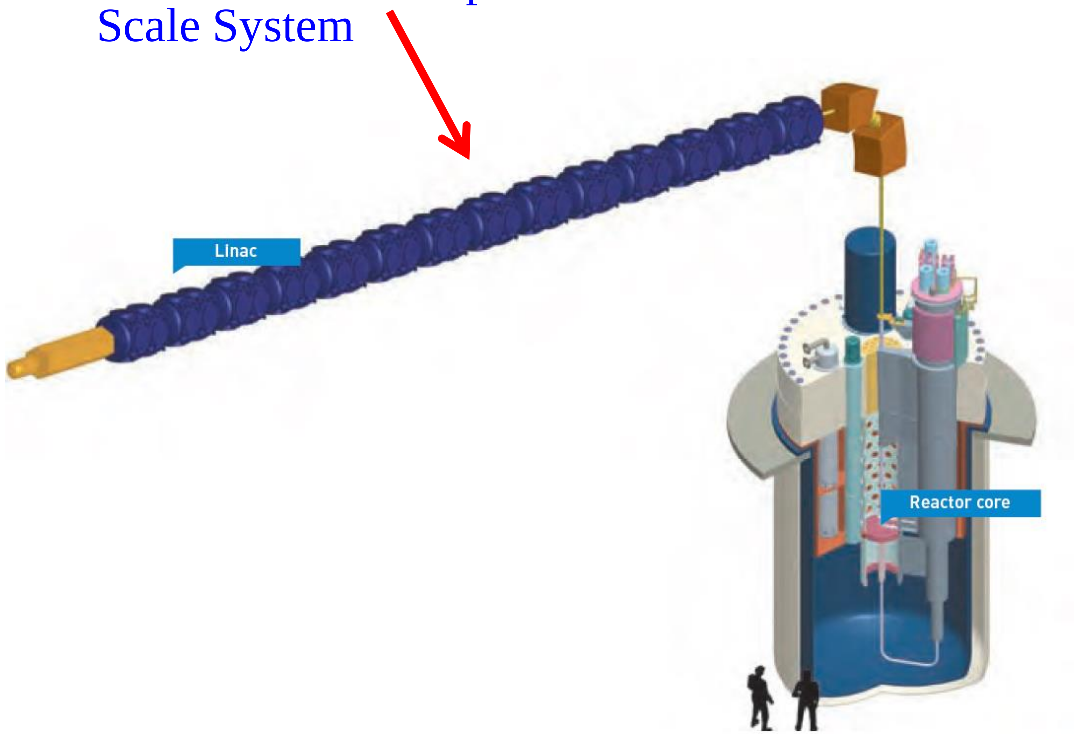
High-power, highly reliable proton accelerator

- ~1 GeV beam energy
- ~1 MW of beam power for demonstration
- Tens of MW beam power for Industrial-Scale System



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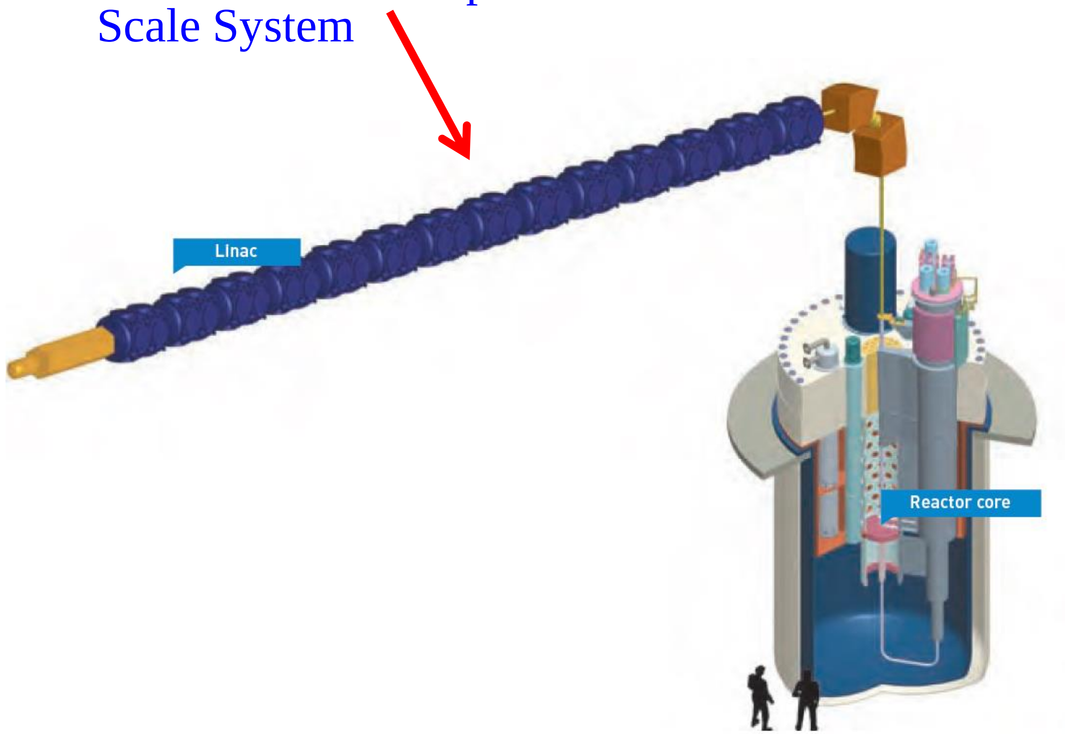
Spallation neutron target system

- Provides external source of neutrons through spallation reaction on heavy metal target



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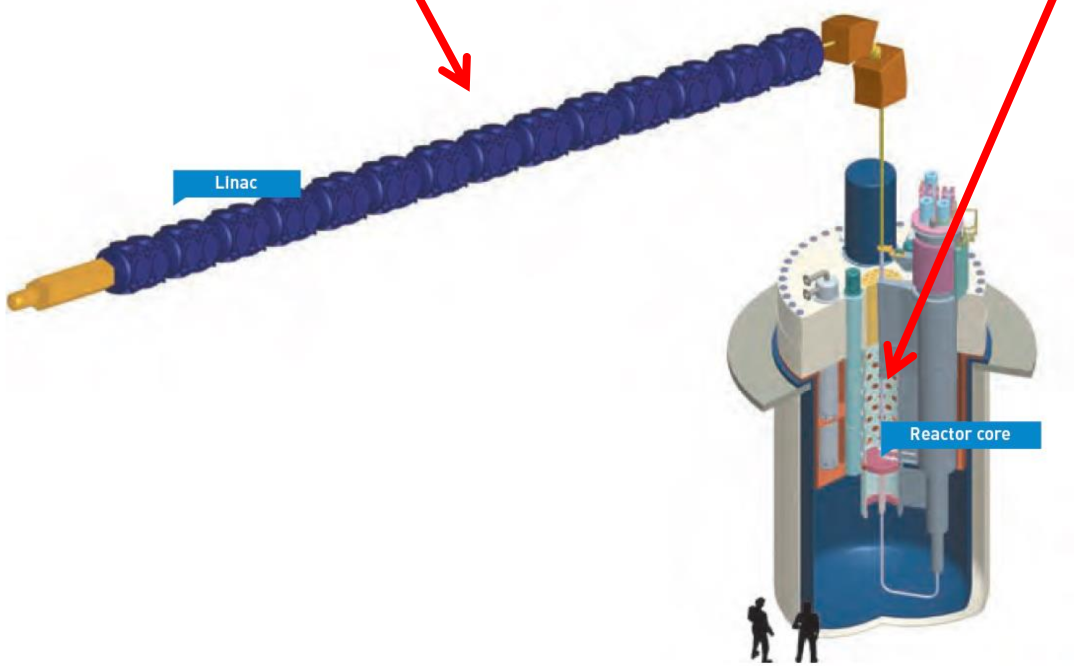

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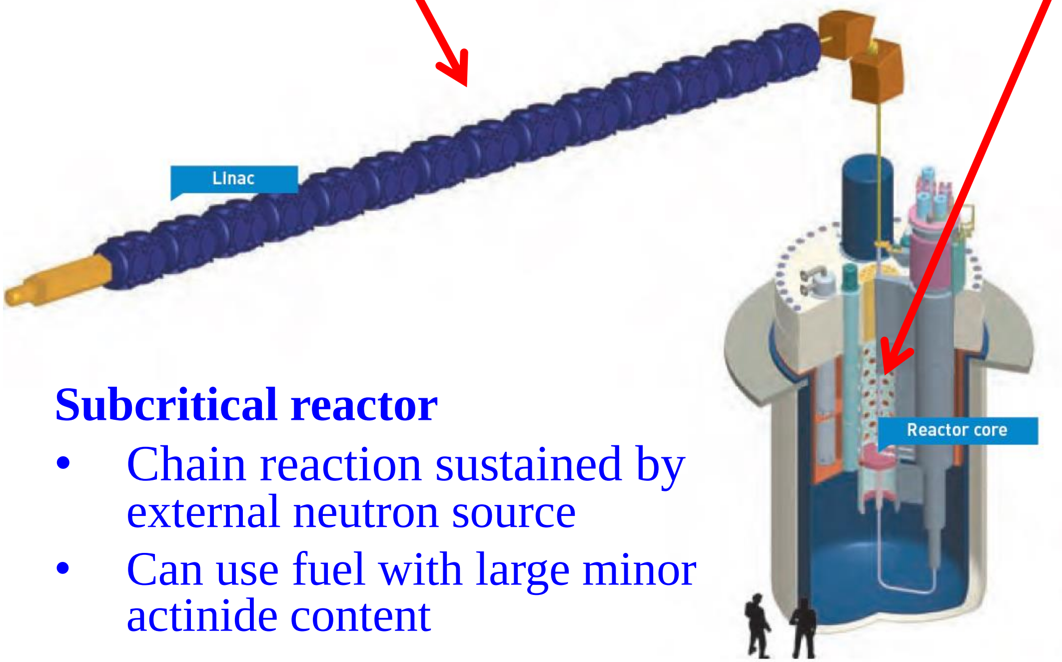

Subcritical reactor
- Chain reaction sustained by external neutron source
- Can use fuel with large minor actinide content

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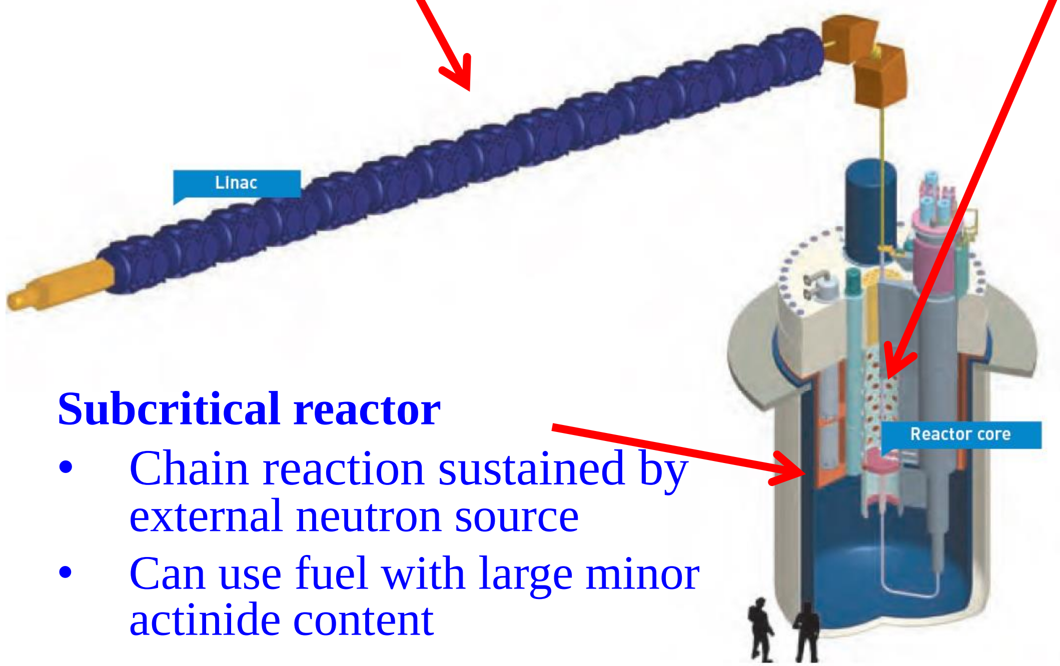

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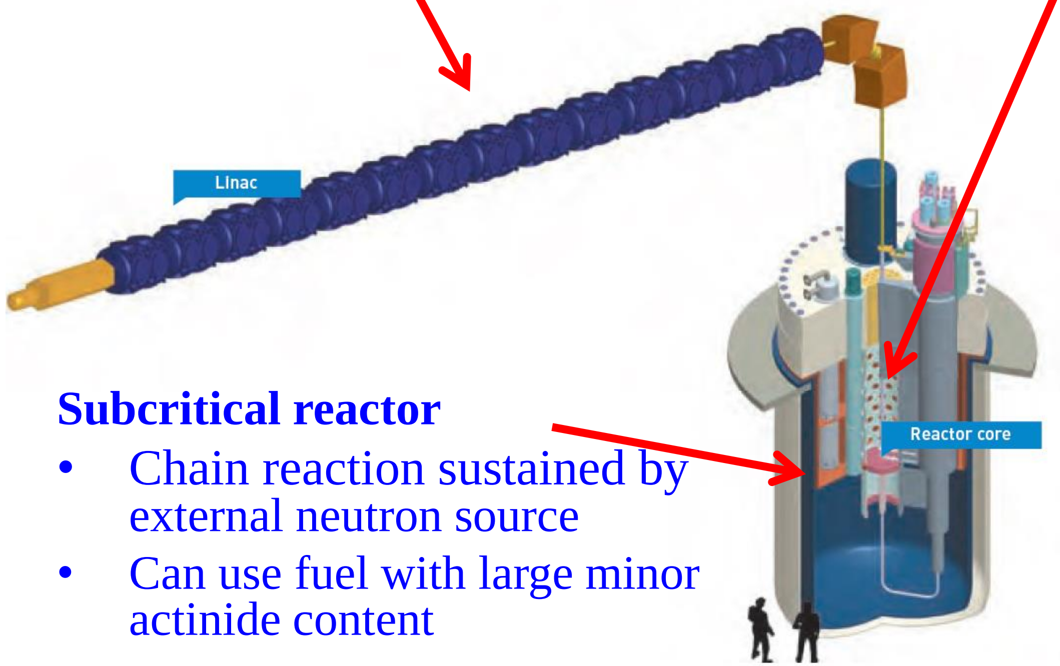

Subcritical reactor

- Chain reaction sustained by external neutron source
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	Transmutation Demonstration	Industrial Scale Transmutation
Beam Power	1-2 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW
Beam trips (t < 1 sec)	N/A	< 25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year
Beam trips (t > 5 min)	< 50/year	< 50/year
Availability	> 50%	> 70%

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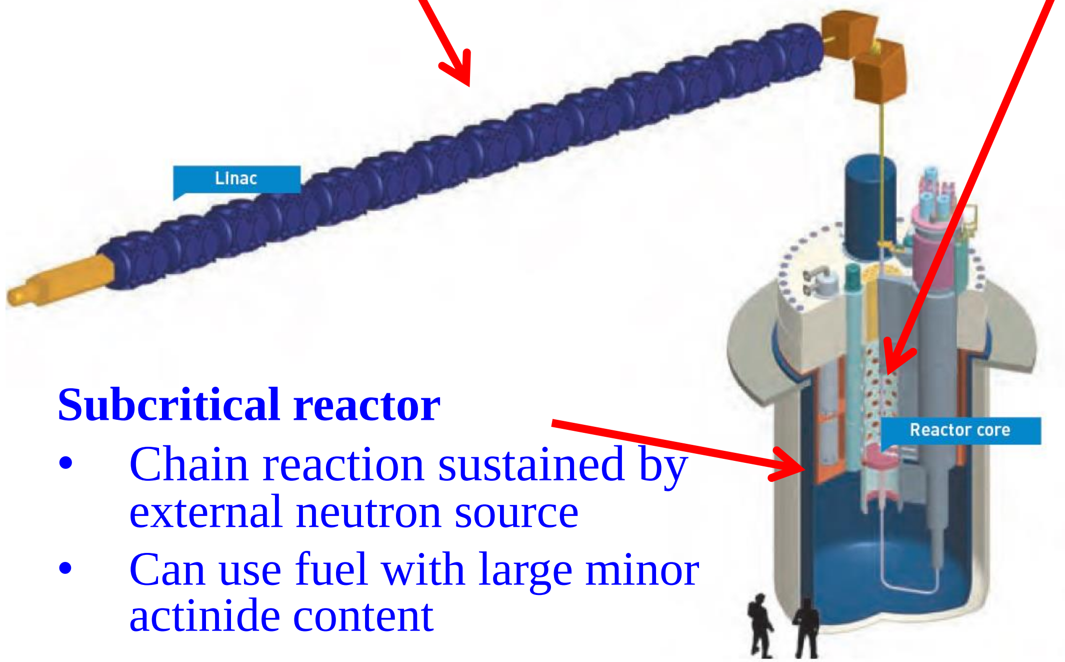

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Extremely High reliability

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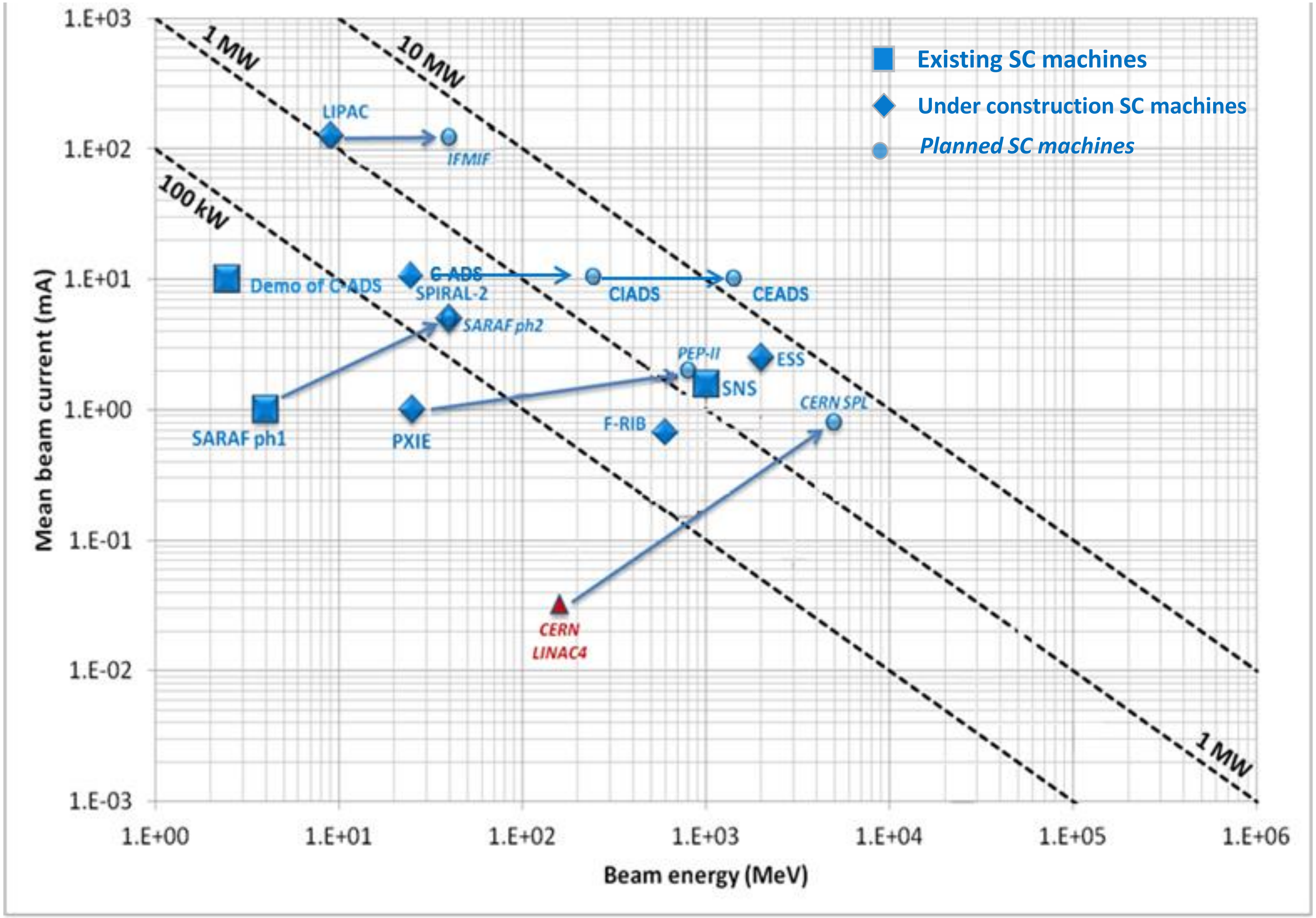
Choice of Accelerator Technology for ADS

- Three technologies have demonstrated MW-class performance
  - Cyclotron – PSI
  - NC Linac – LANSCE
  - SC Linac – SNS
- More than 10 MW beam power to drive GWs reactor, it was concluded that the superconducting RF linear accelerator has the potential than others
  - 5 mA is modest for Cyclotron, difficult to upgrade in energy
  - 100 mA is achievable for sc-linac, upgradable in energy
- Cyclotron at PSI shows very reliability. But redundancy and rapid fault recovery are concerned too. Sc-linac is highly modular and has the capability for achieving very high reliability due to a robust independently-phased-and-amplitude RF system
  - In parallel injectors hot spare and compensation for failure components
  - Rapid recovery in few seconds

Non exhaustive plot about SC Accl.



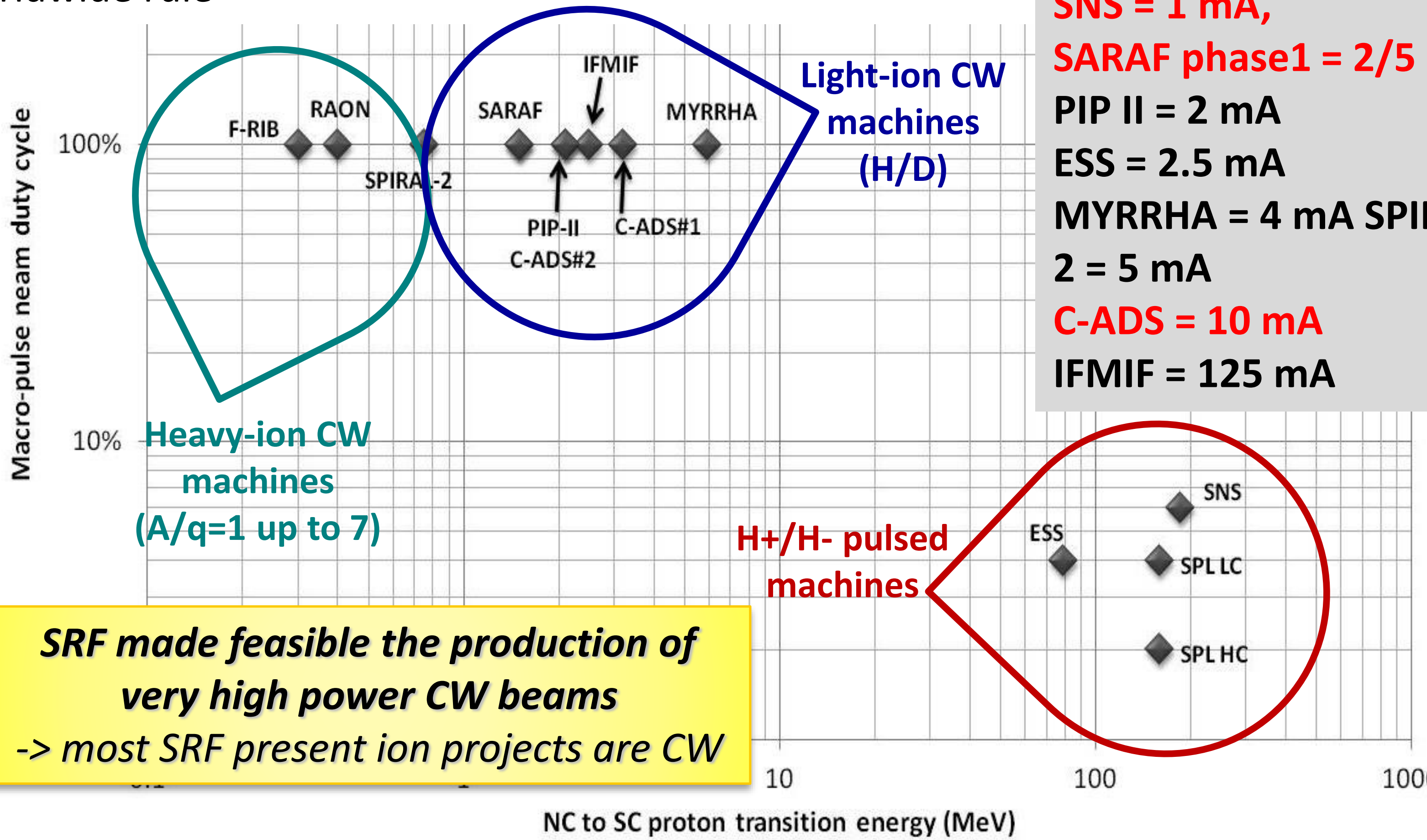
J-Luc Biarrotte, SLHIPP-4, CERN, 15-16 May 2014

High Power SRF Linacs: NC/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

SNS = 1 mA,
SARAF phase1 = 2/5 mA
PIP II = 2 mA
ESS = 2.5 mA
MYRRHA = 4 mA SPIRAL-2 = 5 mA
C-ADS = 10 mA
IFMIF = 125 mA



Non exhaustive plot !

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

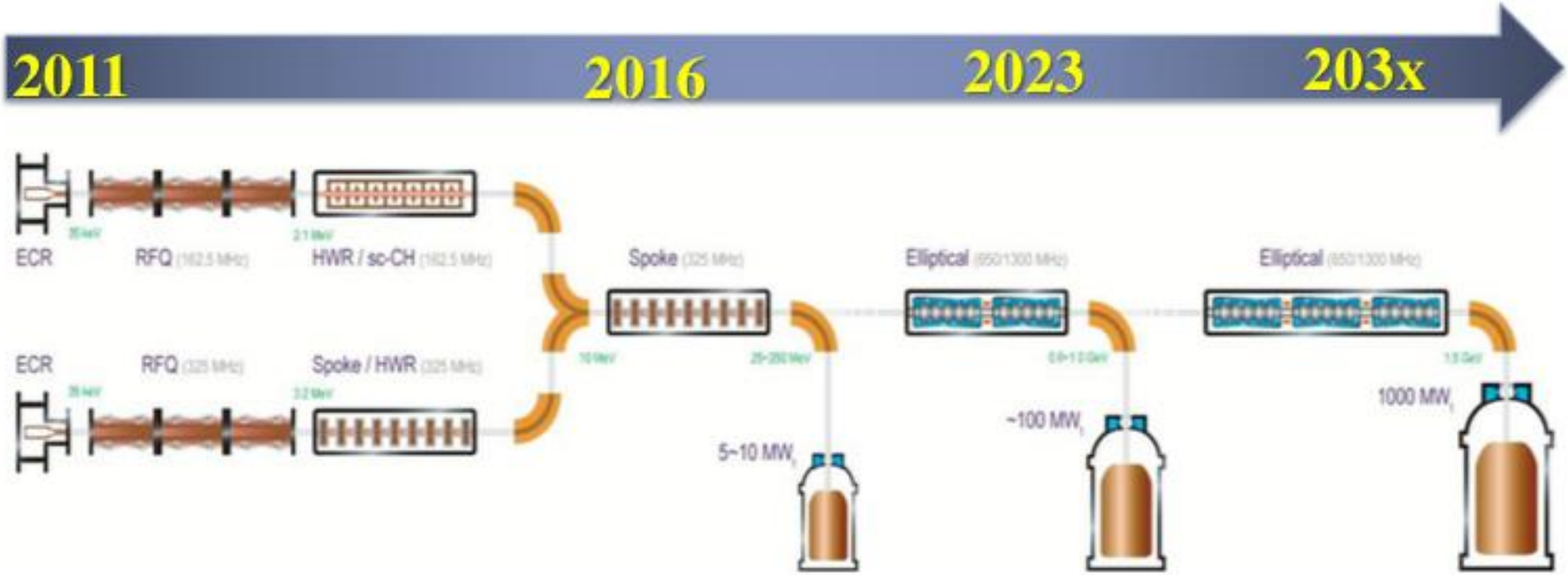
J-Luc Biarrotte, SLHIPP-4, CERN, 15-16 May 2014

Challenge for CW High Power sc-Linac - Non exhaustive list

- **Global optimization on cost, performance and RAMI**
  - ✓High acceleration efficiency, low emittance growth, redundancy scheme, low capital cost, ……
- **Producing high-quality beams (high brightness, low halo) in the injector system at CW, and transporting high power beams while beam loss at a level of <1 Watt/m**
  - ✓ Acceleration of beams from keVs to GeVs with **little emittance growth**, and minimization of **halo growth**
  - ✓ Understanding and control of collective effects that have the potential to generate large-amplitude particles
  - ✓ Systems for **collimation**, beam loss mitigation and machine protection remain very high concerns
  - ✓Reinforced by **SC structures at very low energies** ("soft" beam, small apertures, RFQ tails…)
- **CW operation**
  - ✓**Dynamic heat loads** dominates cryogenics -> Qo is an important cost driver
  - ✓**Thermal issues** on room-temperature elements (couplers, RFQ is non trivial !!!)
  - ✓**Secondary electrons** dominates multipacting and acing (window broken, voltage limit, heat loads)
  - ✓**Operation modes transition** from pulse to CW (or tuning mode to operation), from low current to high current
  - ✓**Diagnostic** failure of components and property of beam very fast and precisely
- **SC cavities at the RFQ output (or nearly) and RFQ itself**
  - ✓**High compactness** is required for SC injectors due to beam dynamics constraints, but compromise is to be found vs operational ease, maintenance, beam diagnostics…
  - ✓**Issues of NC/SC Transition at low energy**, Low-beta SRF is not yet very mature for high current beams

J-Luc Biarrotte, SLHIPP-4
S. Henderson, FNAL Colloquium Feb. 15, 2012

Roadmap of ADS Project in China

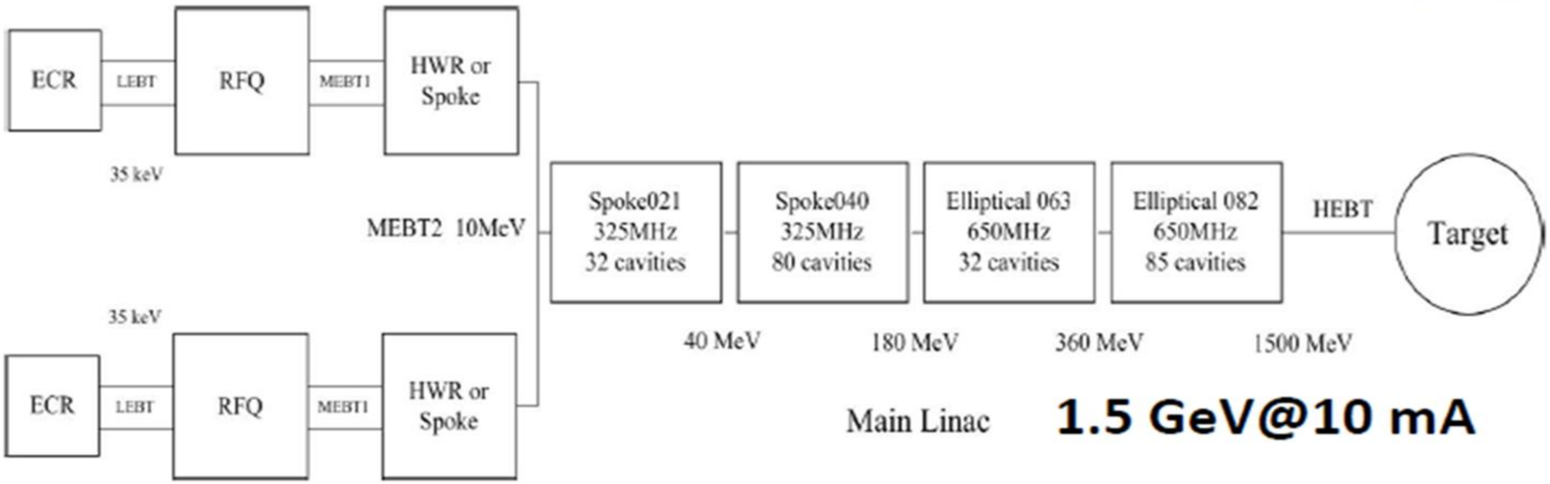


1st Phase	2st Phase	3rd Phase	4th Phase
R&D	CIADS	RESEARCH FACILITY	DEMO FACILITY

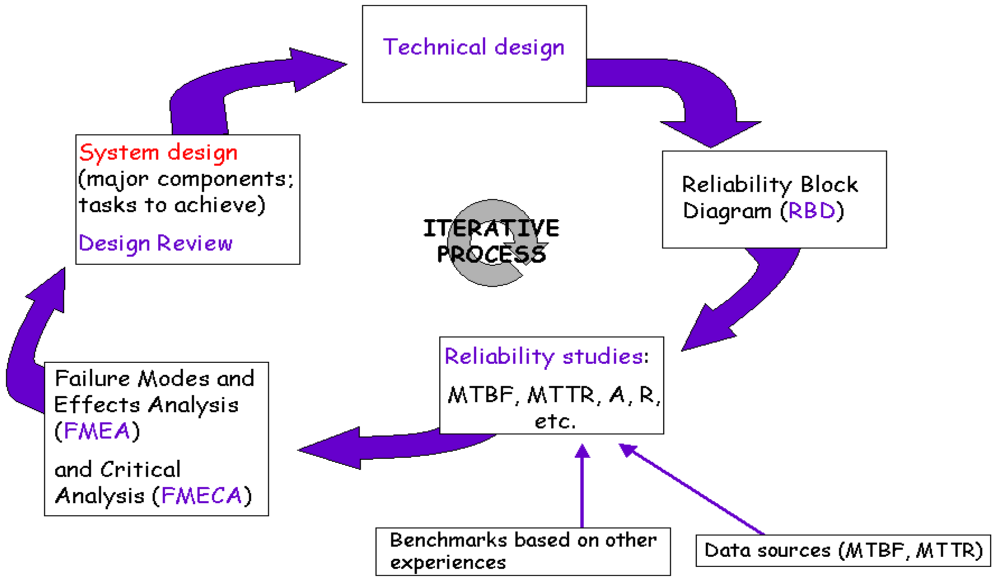
CIADS: INITIAL FACILITY

25MeV@3-10 mA 250MeV@10mA 1.5 GeV@10 mA

Global optimization of SC linac



- High acceleration efficiency
- Low emittance growth
- Less SC cavity family
- Reasonable transverse aperture and longitudinal acceptance
- Good matching between different sections
- ……



Global optimization of SC linac

- Cavity family choice - Normalized TTF

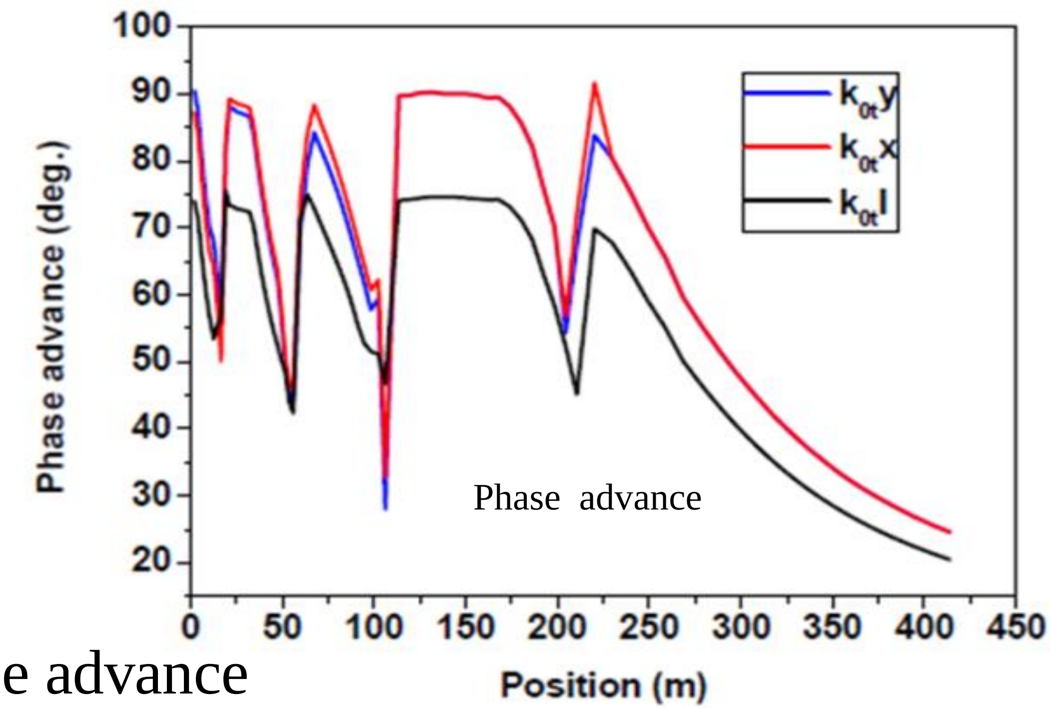
$$\sum_{i=1}^{l}\frac{TTF_i}{l*TTF_{\text{opt}}}+\sum_{i=1}^{m}\frac{TTF_i}{m*TTF_{\text{opt}}}+\cdots+\sum_{i=1}^{n}\frac{TTF_i}{n*TTF_{\text{opt}}}$$

- Periodic structure design optimization

$$K=\frac{\omega q E_0 T}{2c\beta_s\gamma_s^2 W_s}=\frac{\text{Phase advance}}{L}$$

- Match between different section
  - The minimum mismatch factor
  - To keep the “K” smooth at the transition section
- Verify with multi-particles codes
  - Multi-particles tracking with space charge
  - Error simulation

Global optimiz



- Cavity family choi

$$\sum_{i=1}^{l}\frac{TTF_i}{l*TTF_{opt}}+\sum_{i=1}^{m}\frac{TTF_i}{m*TTF_o}$$

- Periodic structure

$$K=\frac{\omega q E_0 T}{2c\beta_s\gamma_s^2 W_s}=\frac{\text{Phase advance}}{L}$$

- Match between different section
  - The minimum mismatch factor
  - To keep the “K” smooth at the transition section
- Verify with multi-particles codes
  - Multi-particles tracking with space charge
  - Error simulation

Optimizations of Injector II as example

Objective

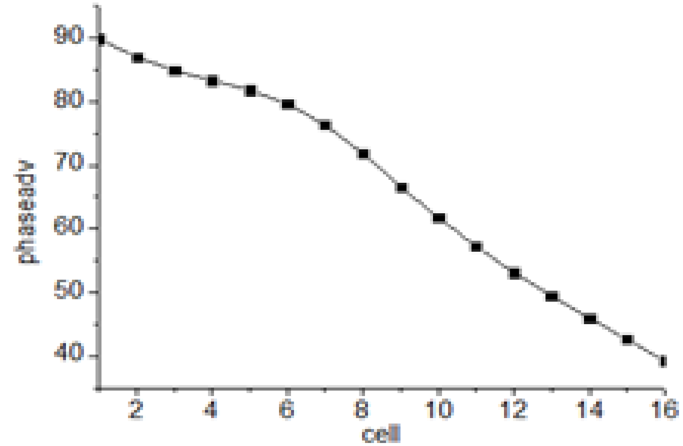
$$f_x = \frac{1}{NM}\sum_{i=2}^{N-2}\sum_{j=1}^{M}(d^2\sigma_{i,j})$$

Algorithm

Particle swarm optimization

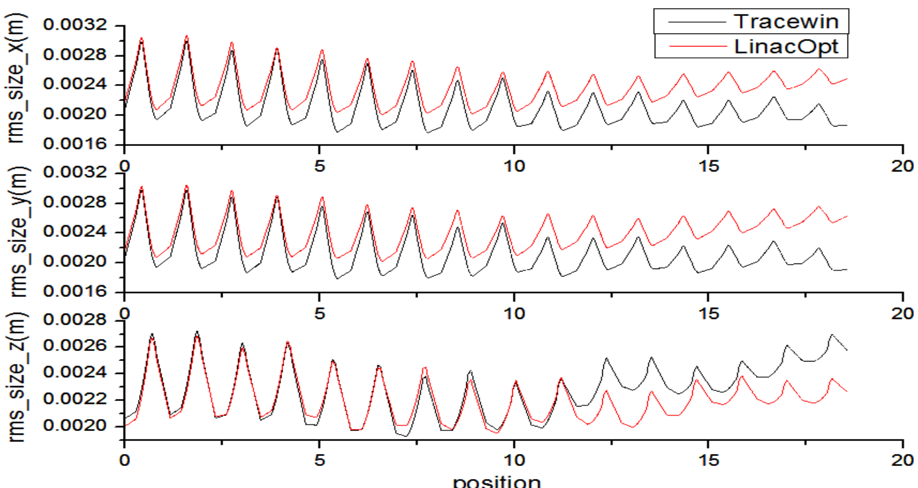
Constraint

- ✓ Limited Cavity voltage
- ✓ Energy output more than 10MeV



Phase advance of Optimization Results

Growth (%)	Tracewin	LinacOpt
ε_{x_rms}	6.17	5.60
ε_{x_max}	110.68	76.78
ε_{y_rms}	5.99	3.46
ε_{y_max}	148.95	121.53
ε_{z_rms}	5.60	5.43
ε_{z_max}	92.97	32.33

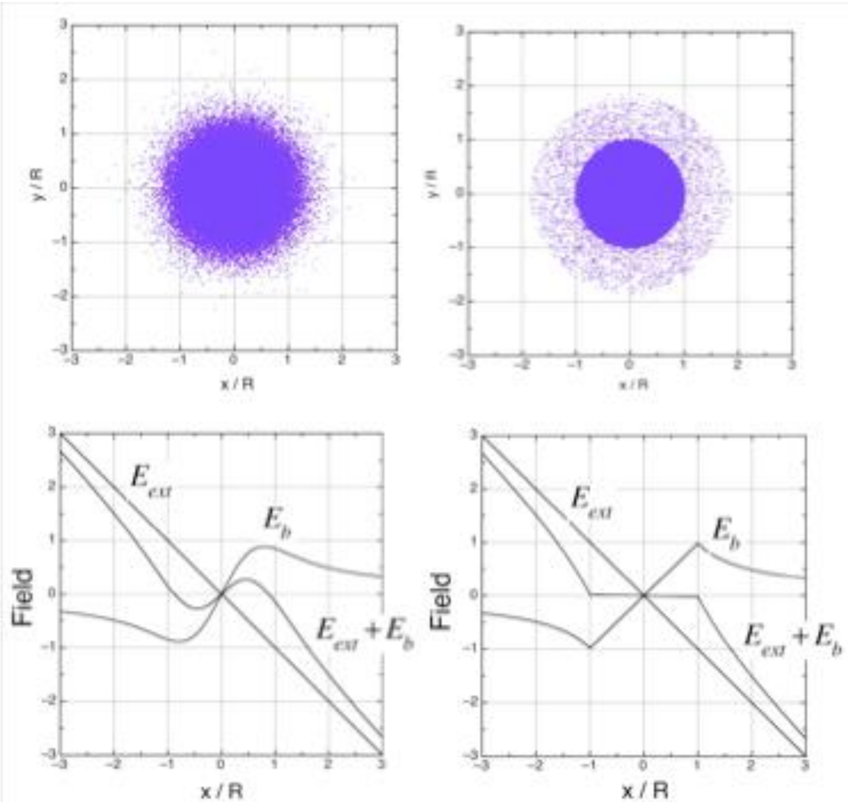


Rms envelope comparison of two design

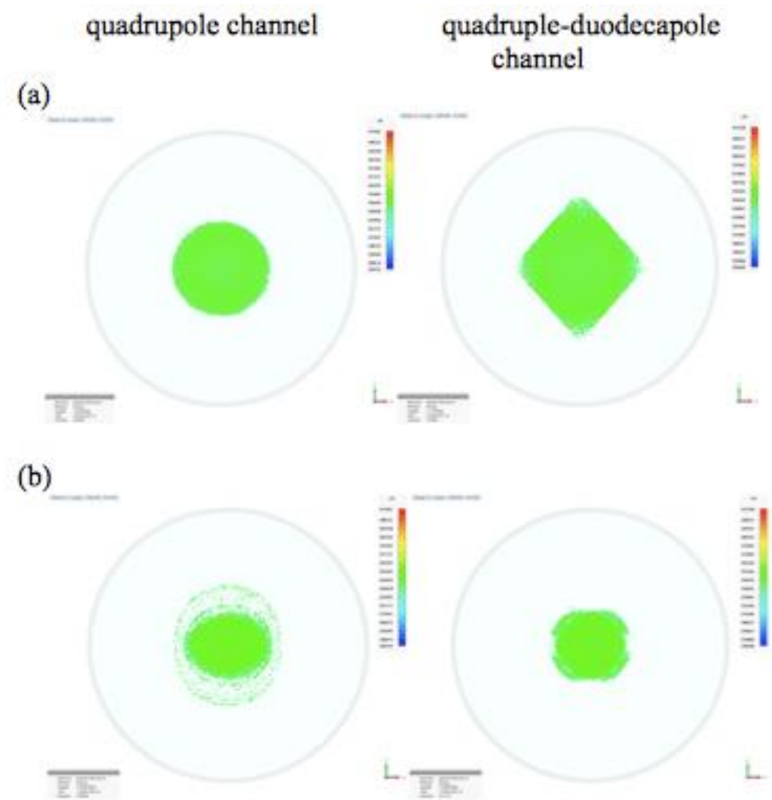
Challenge for beam physics – Beam Loss control

- **Beam halo control**
  - Suppression with nonlinear field
  - Collimation
  - Matching
- **Beam instability**
  - HOM
  - Space charge driven resonance
  - Parameter driven resonance
- **Fault compensation**
  - Local and Global

Beam Halo Suppression



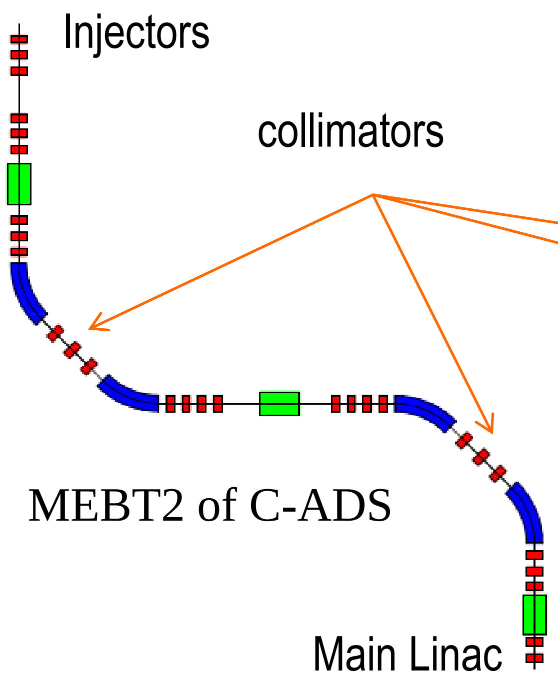
(left) Initial and (right) final particle distribution of a high-brightness beam in a continuous focusing channel: Eb – space charge field, Eext –focusing field.

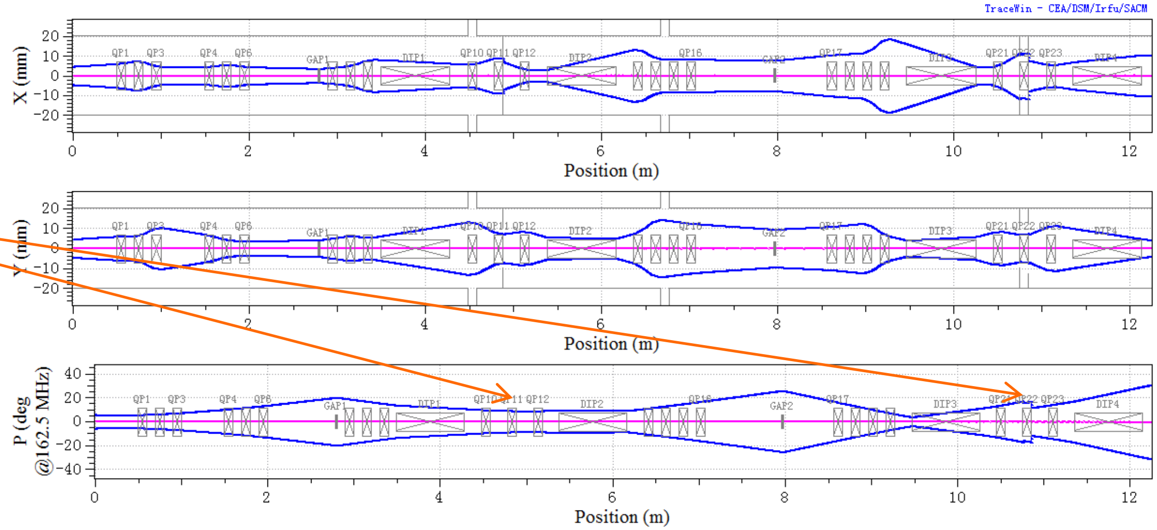


(a) initial and (b) final x-y particle distributions in a focusing channels containing 30 focusing FODO periods.

Yuri K. Batygin， Chao Li，NONLINEAR OPTICS FOR SUPPRESSION OF HALO FORMATION IN SPACE CHARGE DOMINATED BEAMS，IPAC14

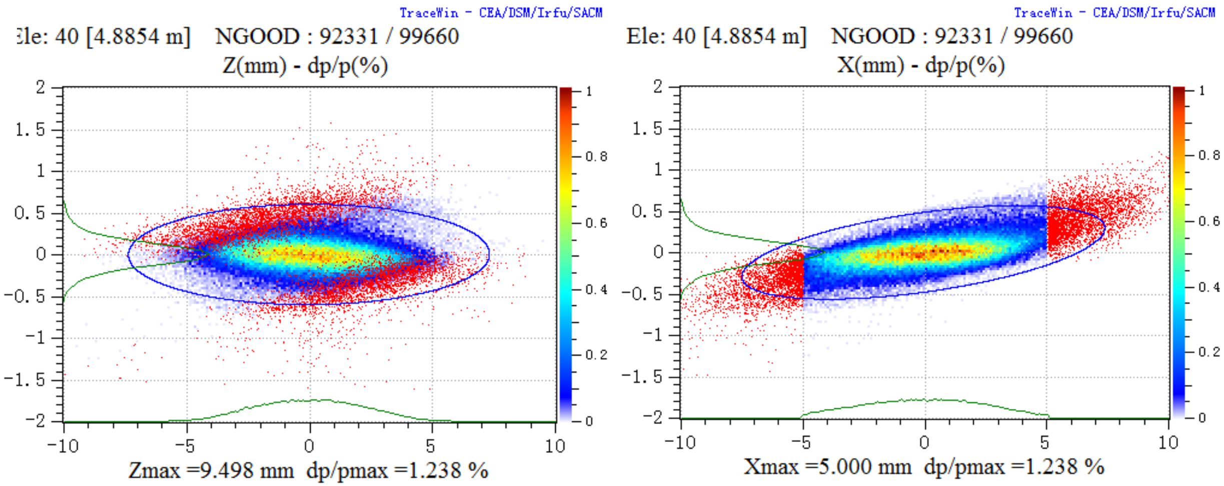
Longitudinal Beam halo collimation





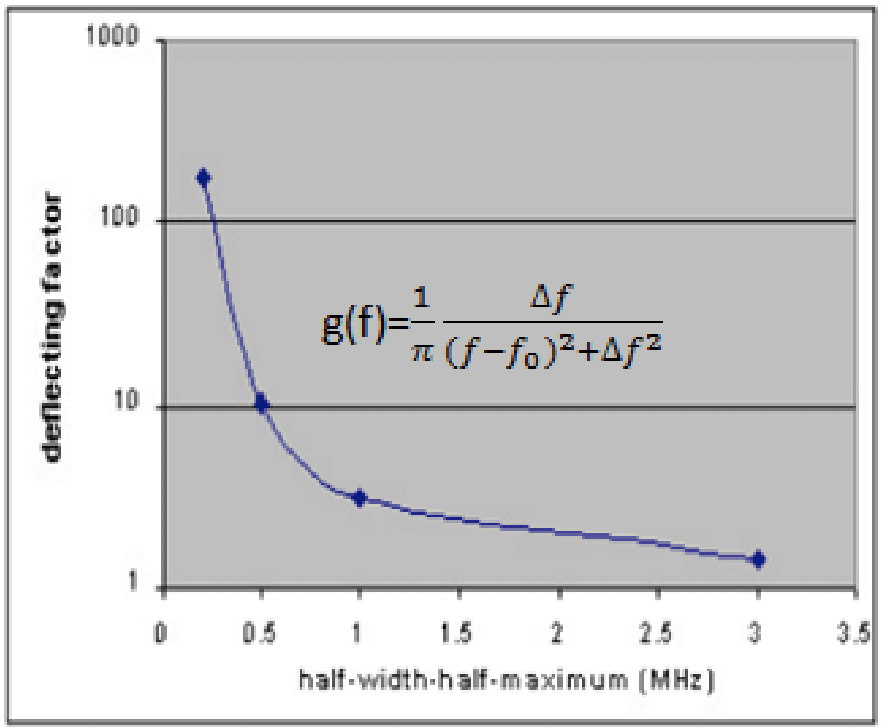
Collimators located in the dispersion section with 90 deg phase advance

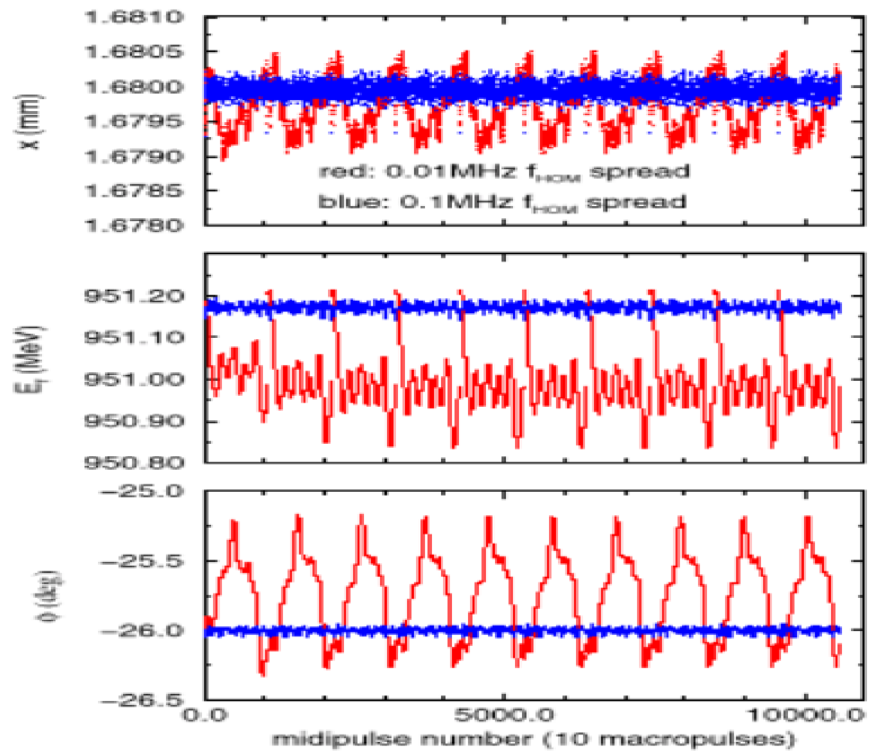
H Jia, Bill Ng, X Zhang



Collimated particles (red) at Z- dp/p (left) and X-dp/p (right) phase space

Beam instability - BBU





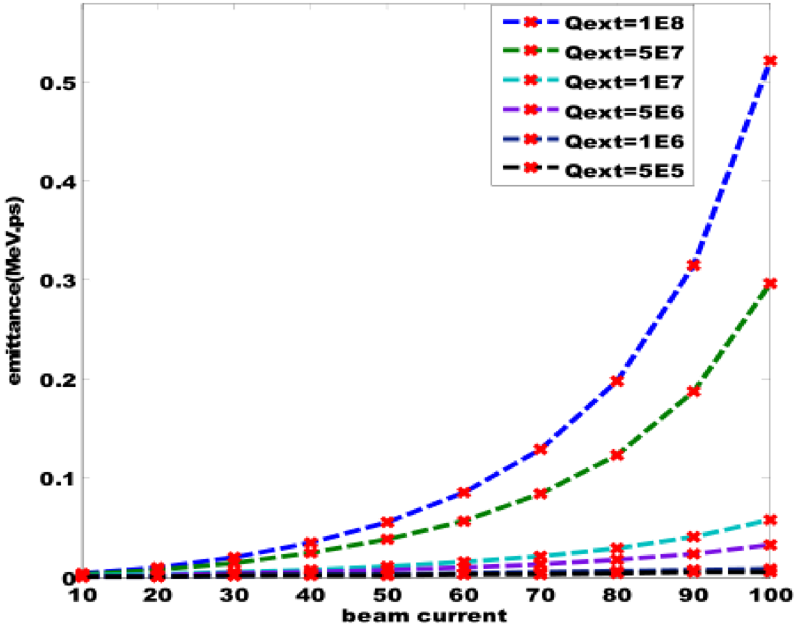
$\Delta x \approx 0.001\text{mm}$ $\Delta E_f \approx 0.2\text{MeV}$ $\Delta \phi \approx 1^\circ$

BBU issue is not a concern for SNS SC LINAC.

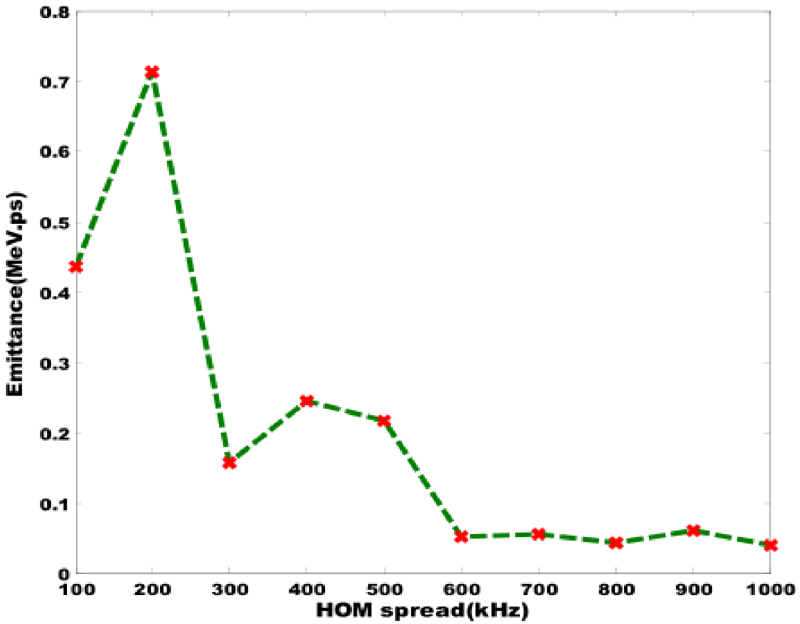
D. Jeon , et al ," TRANSVERSE BEAM BREAK-UP STUDY OF SNS SC LINAC", Proceedings of the 2001 Particle Accelerator Conference, Chicago

C-ADS longitudinal beam instability caused by HOM

Evaluation Criterion: $$\varepsilon = \pi\sqrt{< dE^2 >< dt^2 > - < dE \cdot dt >^2}$$



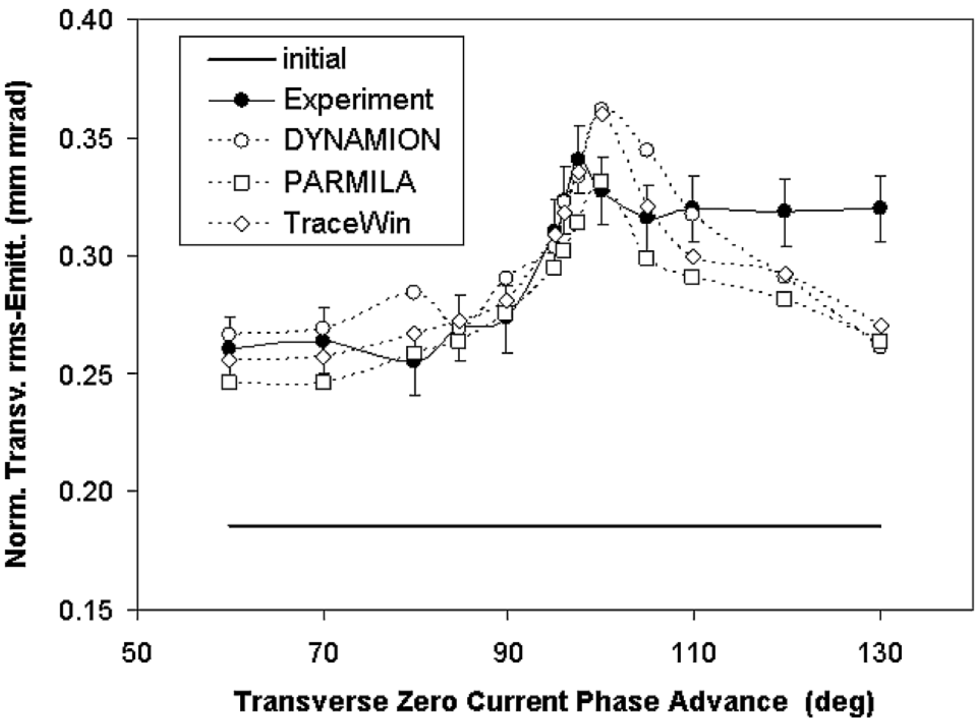
Diffusion for different beam current and different damping condition Qext @$\Delta f = 100kHz$

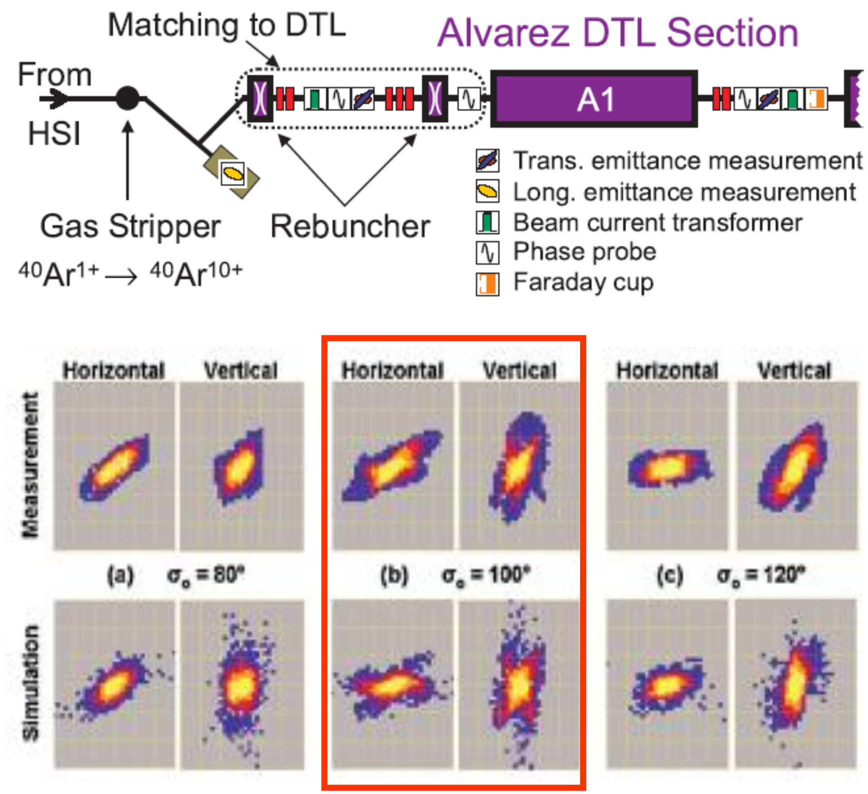


Diffusion against different width of the Gaussian distributed HOM frequency spread @I=100mA, Qext=1e8

Simulation results monopole modes induced longitudinal instability is not a problem if HOM frequency spread is greater than 1MHz.

P. Cheng , et al, STUDY OF THE C-ADS LONGITUDINAL BEAM INSTABILITIES CAUSED BY HOMS, Proceedings of IPAC2013, Shanghai, China



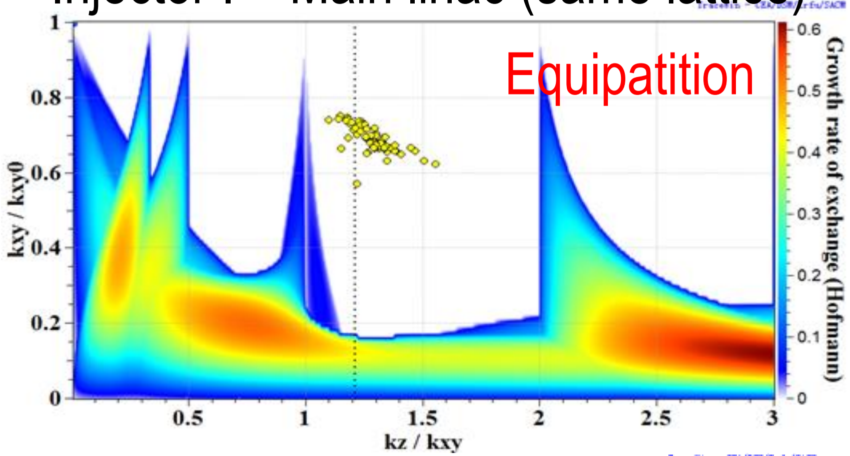


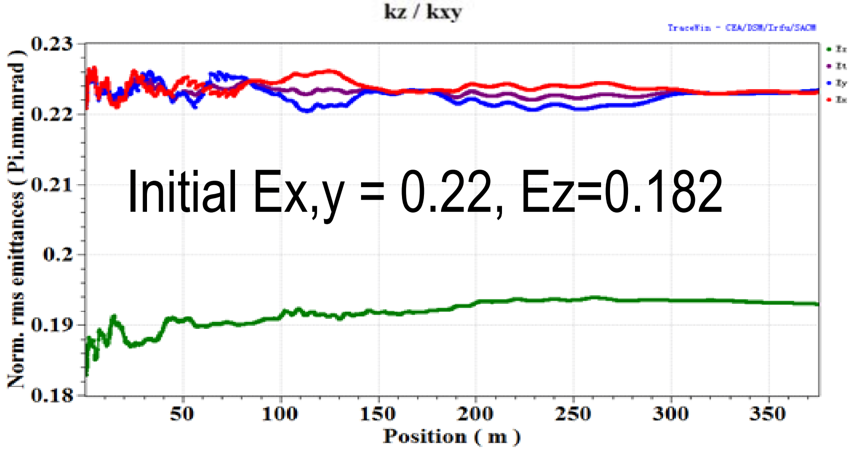
Experimental Evidence of the 90^0 Stop Band in the GSI UNILAC as part of EU-HIPPI code benchmarking campaigns 2003-08
L. Groening et al. PRL 102, 234801 (2009)

Ingo Hofmann,ESS Beam Dynamics Workshop,Lund, October 31 - November 1, 2011

Equipatition

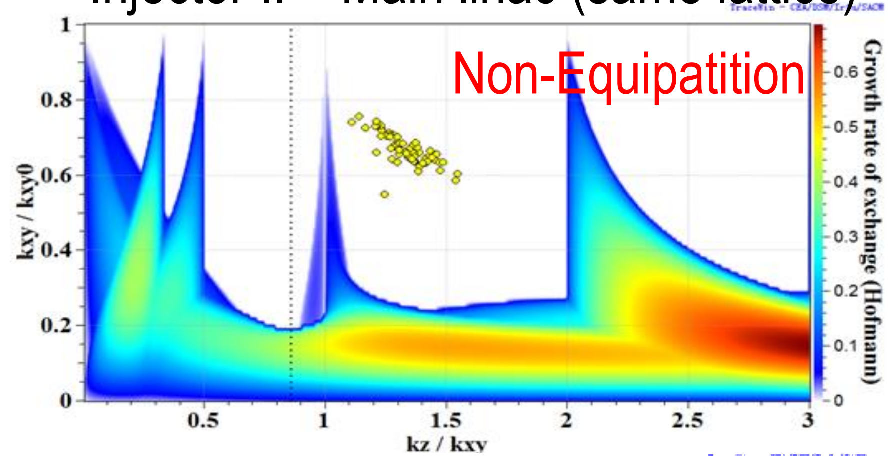
Injector I + Main linac (same lattice)

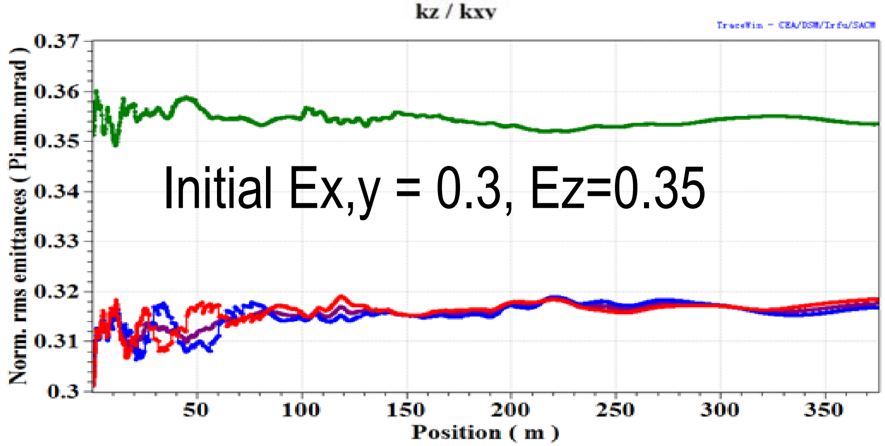




Ex (%)		Ey (%)		Ez (%)	
RMS	99%	RMS	99%	RMS	99%
1.4	4.4	1.5	5.4	7.2	5.0

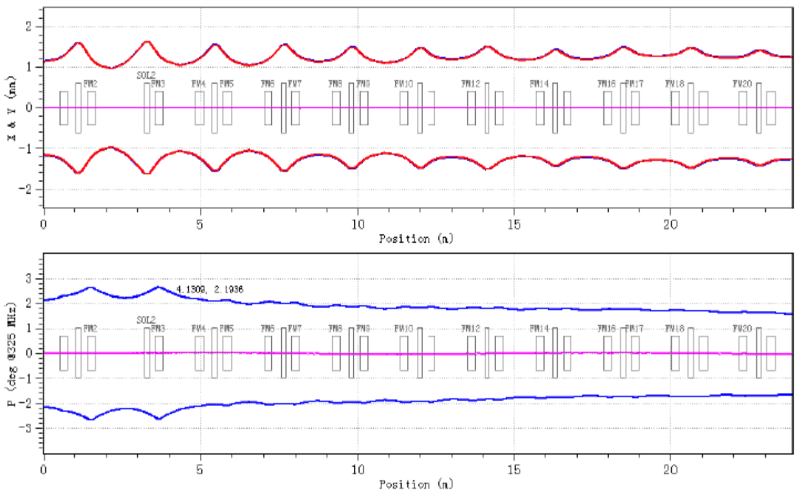
Injector II + Main linac (same lattice)

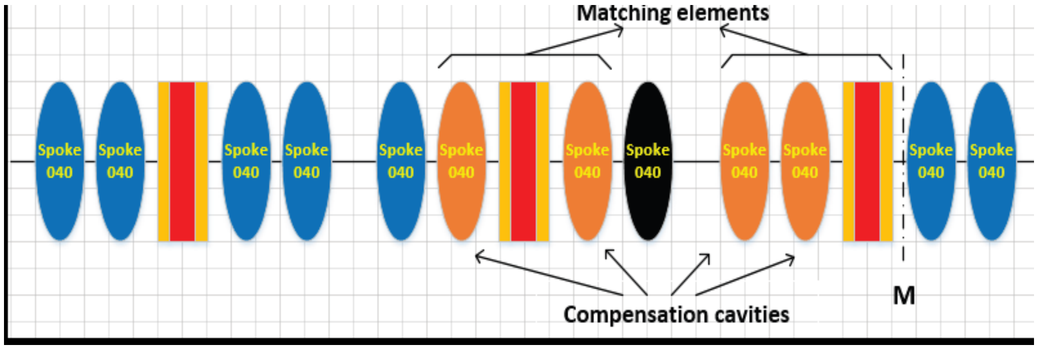




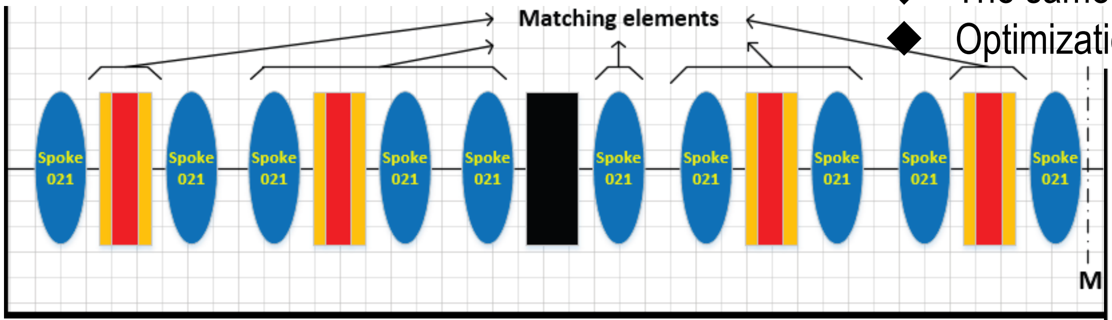
Ex (%)		Ey (%)		Ez (%)	
RMS	99%	RMS	99%	RMS	99%
5.6	14.0	6.2	14.0	1.0	4.3

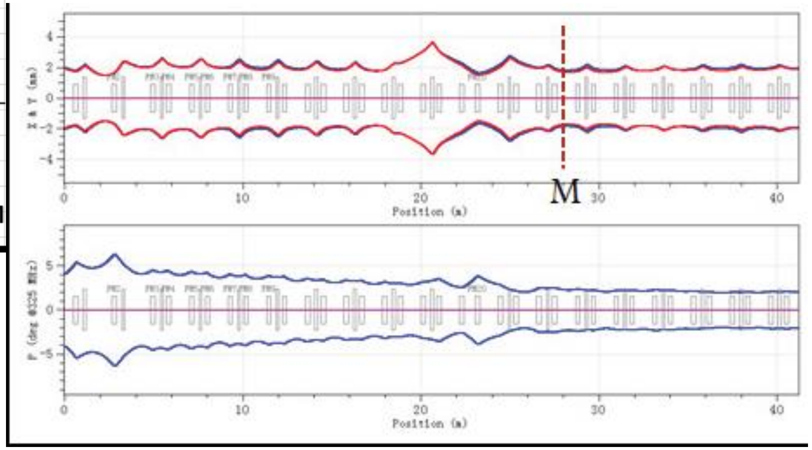
Fault compensation - local





- One Cavity faulty
- The same T at location M(Key point)
- The same energy at location M
- The same TWISS parameters at location M
- Optimization with Genetic Algorithm





- One Solenoid faulty
- The same T and energy at location M
- The same TWISS parameters at location M
- Small envelope oscillations in the matching section

B. Sun, IPAC 2014

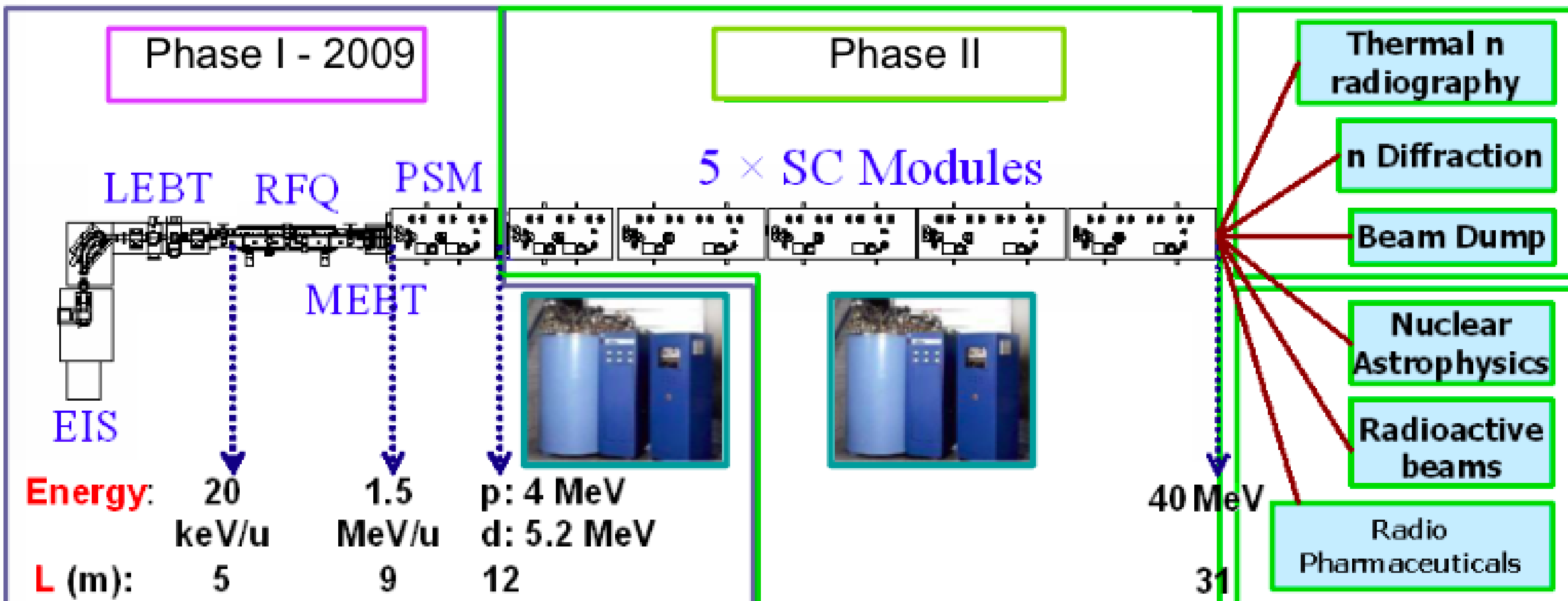
The challenge of technology and some experiences

- Hydrogen transfer and dynamic vacuum gets worse due to ion source and beam loss
- Control of current and duty factor of beam from ion source, operation mode transmition
- High gradient RF at CW is hard to achieve, MP and arcing due to secondary electrons and FE
  - ion source trip, RFQ, windows broken of couplers, sc cavity at CW, dynamic heat loss, and so on.
- Beam dump and Non interceptive beam diagnostic, to get 6-D phase space by using BPM is necessary
- Detection of machine protection
- ……

SARAF Accelerator Complex

Parameter	Value	Comment
Ion Species	Protons/Deuterons	M/q ≤ 2
Energy Range	5 – 40 MeV	Variable energy
Current Range	0.04 – 5 mA	CW (and pulsed)
Operation	6000 hours/year	
Reliability	90%	
Maintenance	Hands-On	Very low beam loss

176 MHz



SARAF Phase I Status

2012 Beam Operation

The accelerator was used for beam studies or for delivering beams for experiments at any available opportunity. So far the most intense period of beam operation consisted of nine working days of continuous (excluding a weekend) operation, which included four days of collection of 0.25 mA, 3.6 MeV CW beam of 4 W/mm^2 heat flux on a thin foil target and five days of tests of beam diagnostics from GANIL with 0.1-1 mA, 2.2 MeV CW and pulsed beams. Five cavities were used for the former beam and only three for the latter.

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2014 Beam Operation

ion	E (MeV)	I (mA)	DC (%)	time (h)	Comments
p	3.6	1.6	100	1	pin beam dump test
p	2.0	2.1	100	4	max. current test
p	1.92	1.5	100	10	LiLiT experiments
p	3.7	0.3	100	50	foil target tests
p	4.0	0.5	160 ns 500 Hz	2	LiLiT 2 MeV neutrons
d	5.6	0.01	1	20	cross section meas.

SARAF Phase I Status

2012 Beam Operation

The accelerator was used for beam studies or for delivering beams for experiments at any available opportunity. So far the most intense period of beam operation consisted of nine working days of continuous (excluding a weekend) operation, which included four days of collection of 0.25 mA, 3.6 MeV CW beam of 4 W/mm^2 heat flux on a thin foil target and five days of tests of beam diagnostics from GANIL with 0.1-1 mA, 2.2 MeV CW and pulsed beams. Five cavities were used for the former beam and only three for the latter.

2014 Beam Operation

Record:
3.6 MeV, 1 mA, CW
2.0 MeV, 2.1 mA, CW

ion	E (MeV)	I (mA)	DC (%)	time (h)	Comments
p	3.6	1.6	100	1	pin beam dump test
p	2.0	2.1	100	4	max. current test
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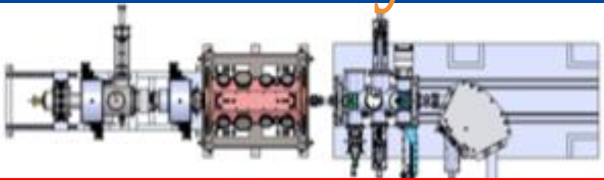
SARAF Phase I linac in 2012, WEIOB02 Linac2014

Commissioning Plan of Demo Linac Facility of C-ADS (base on injector II)

1



- ECRIS + LEBT + 560keV RFQ prototype
- Validate LIS+LEBT+RFQ design. Learn experiences.
- Completed, 2013

2

- ECRIS + LEBT + RFQ + MEBT + TCM1, 2.5 MeV
- RFQ commissioning, validate CM design.
- Ongoing, beam commissioning in Sept. 2014

First beam on Oct. 1st, sc cavity failure on Oct. 10th.

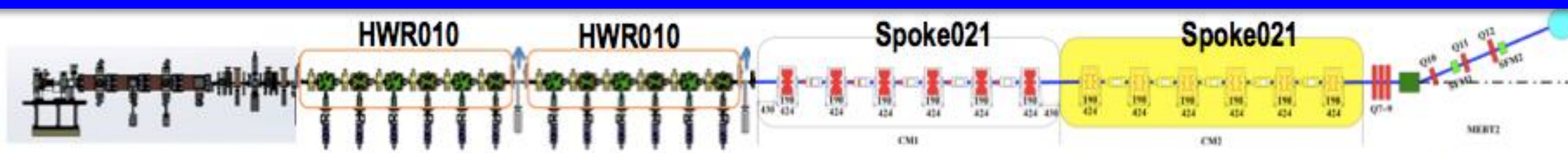
3

- ECRIS+LEBT+RFQ+MEBT+CM6, 5 MeV
- Beam commissioning in March 2015

4

- ECRIS + LEBT + RFQ + MEBT + 2xCM6 +HEBT, 10 MeV
- Dec. 2015—Feb. 2016

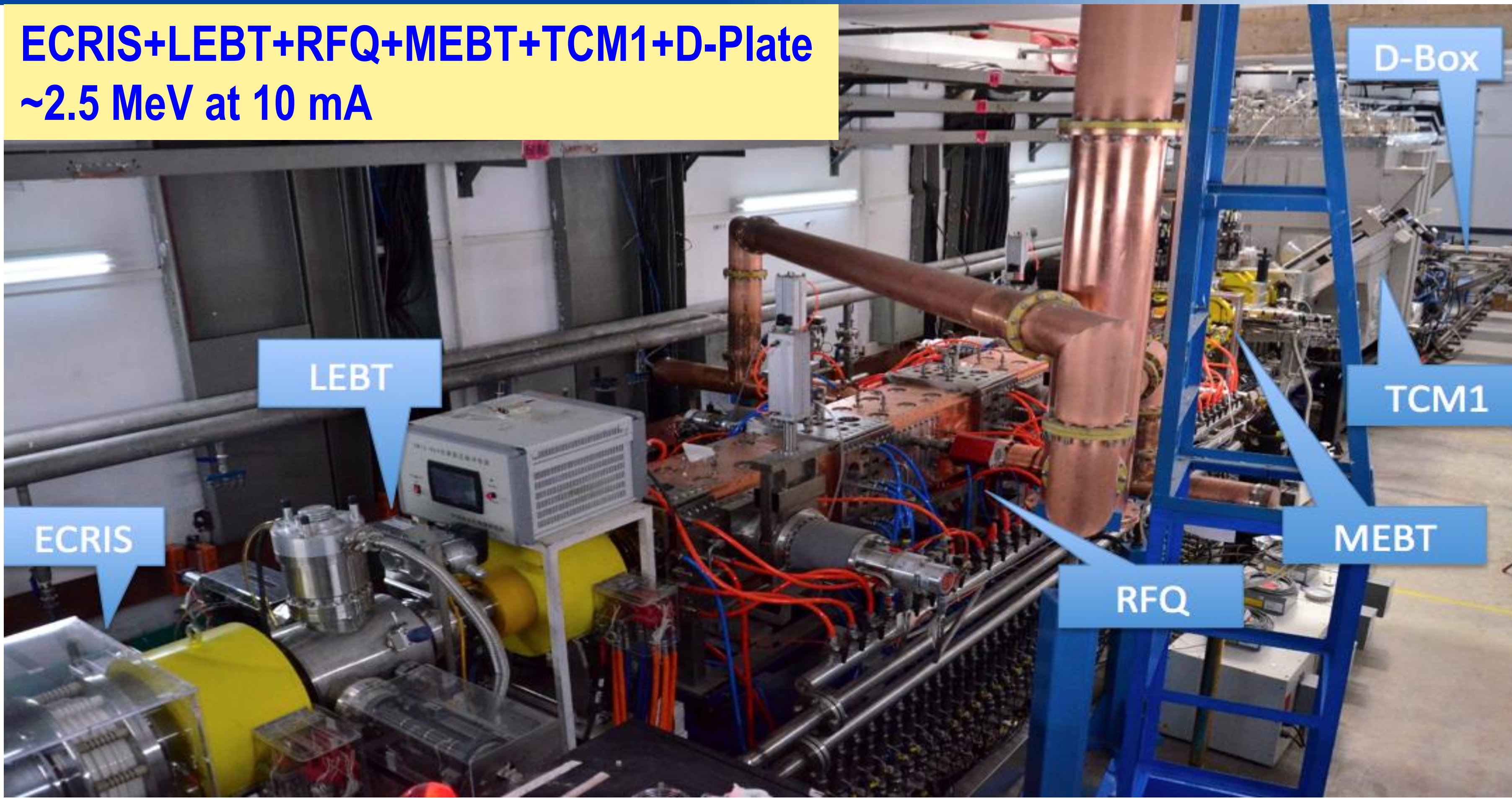
5



- ~25 MeV, Dec. Sept. 2016 - 2017

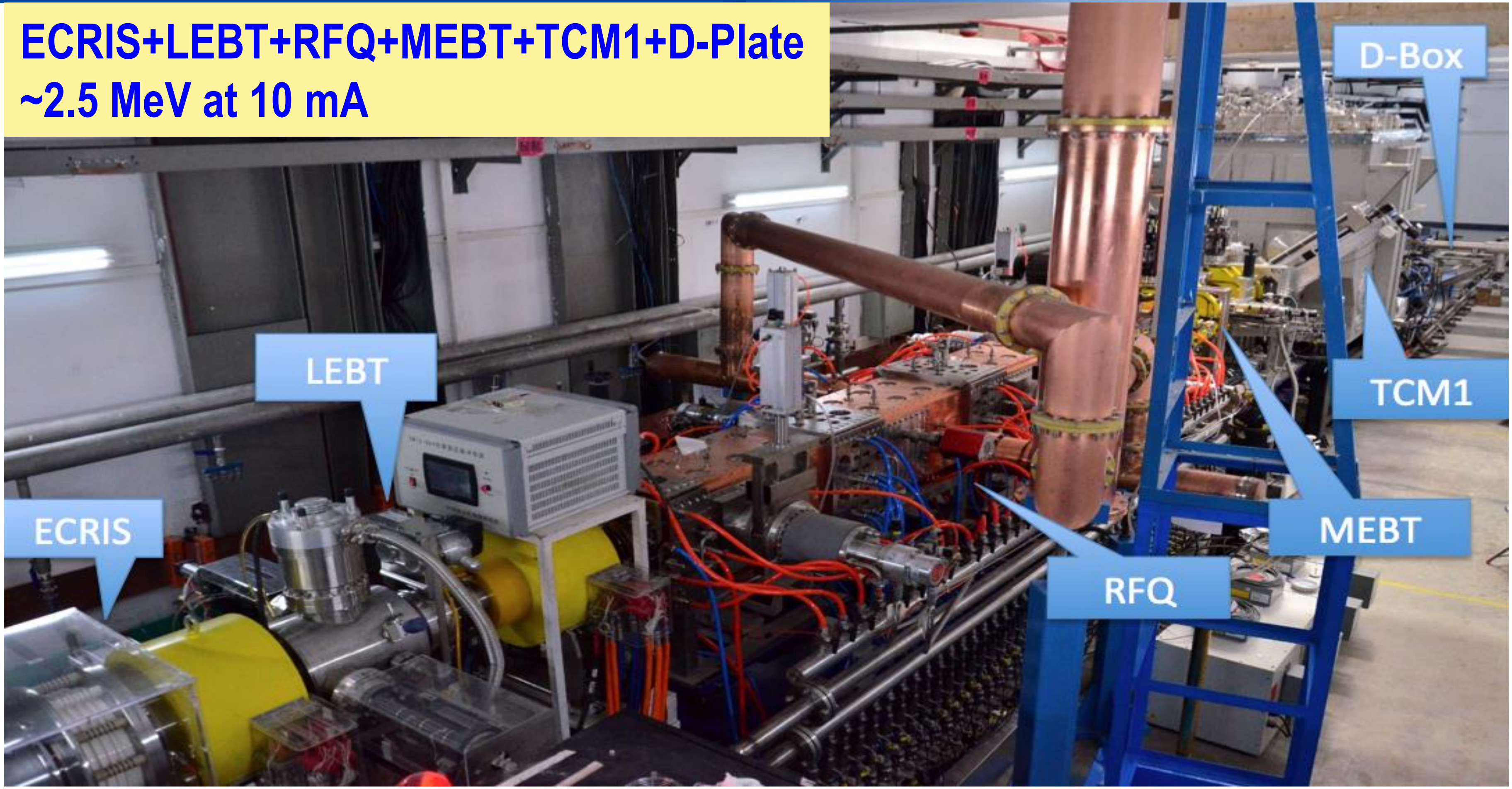
Status of Demo Facility of C-ADS

ECRIS+LEBT+RFQ+MEBT+TCM1+D-Plate
~2.5 MeV at 10 mA



Status of Demo Facility of C-ADS

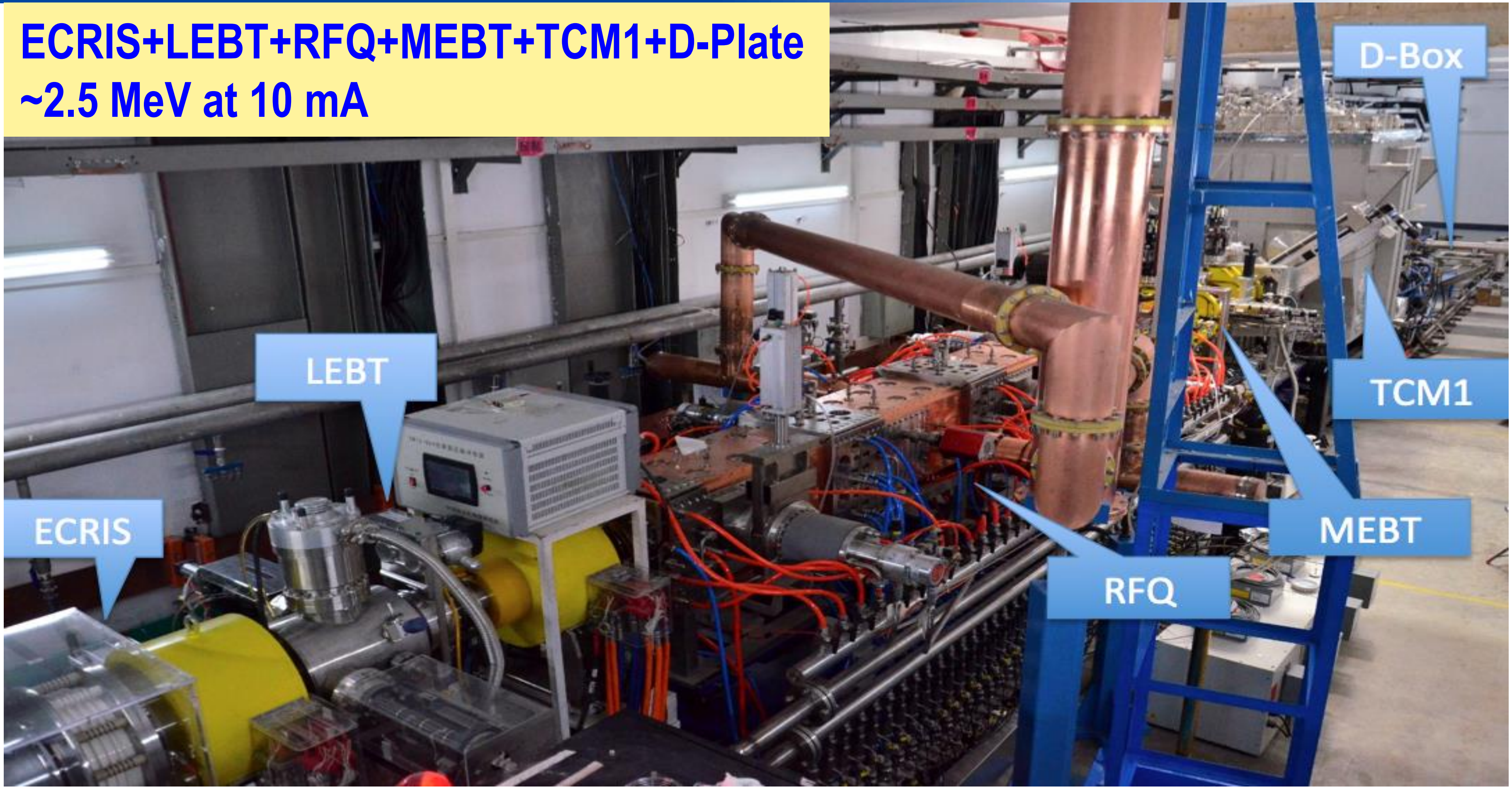
ECRIS+LEBT+RFQ+MEBT+TCM1+D-Plate
~2.5 MeV at 10 mA



- **RFQ operated successfully at 2.15 MeV/10 mA/CW mode, many times in 20 days. the record was 4.5 hours @ 10 mA and 6 hours @ 6 mA. The rms emittance is ~0.24 pi.mm.mrad, dp/p is 1.9%, transmission effective is 97%. Total operation time is ~520 hours including CW@10mA around 10 hours.**

Status of Demo Facility of C-ADS

ECRIS+LEBT+RFQ+MEBT+TCM1+D-Plate
~2.5 MeV at 10 mA



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- **MEBT and TCM (HWR010) operated at 2.3 mA/2.6 MeV/2 ms/50 Hz pulse beam， Transmission 97%. Total operation time is ~ 60 hours. The record was 2.3 mA/2.6 MeV/1 ms/50 Hz beam lasted for 7 hours. Failure due to gas leak and others on Oct. 10th.**

Issues of hydrogen transfer at SARAF

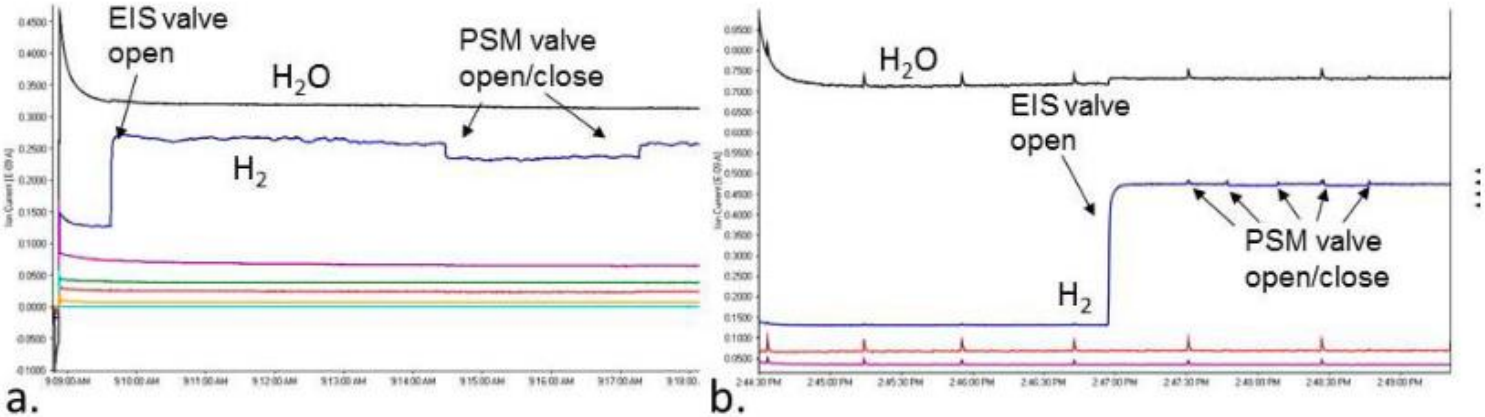


Fig. 13. Log of the RGA installed at the first MEBT chamber. Effect on hydrogen partial pressure at opening of the EIS and PSM valves are shown for the original configuration (a) and after replacement of the ion pump by a turbo pump (b).

The hydrogen and residual gas will frozen on the RF surface of sc cavity. It is contaminated again and causing multipacting.

The reason of sc cavity failure!?

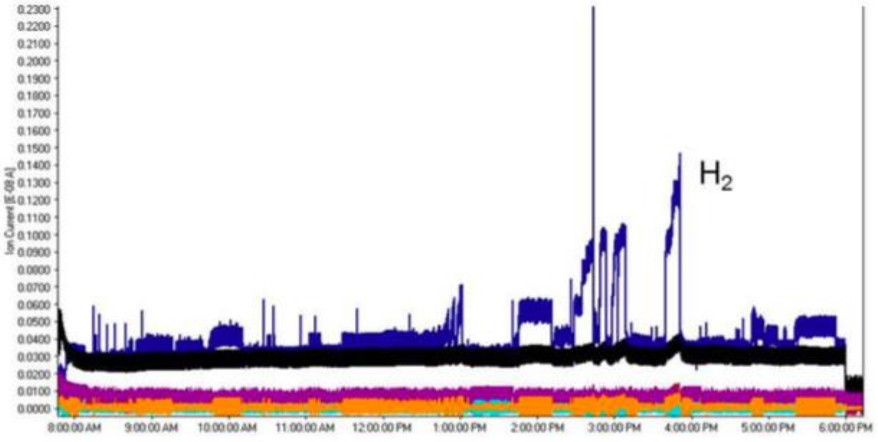
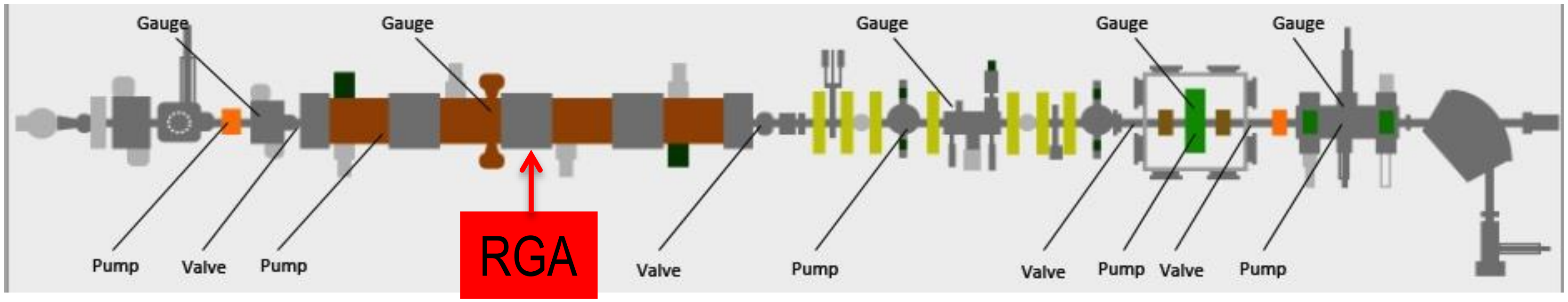
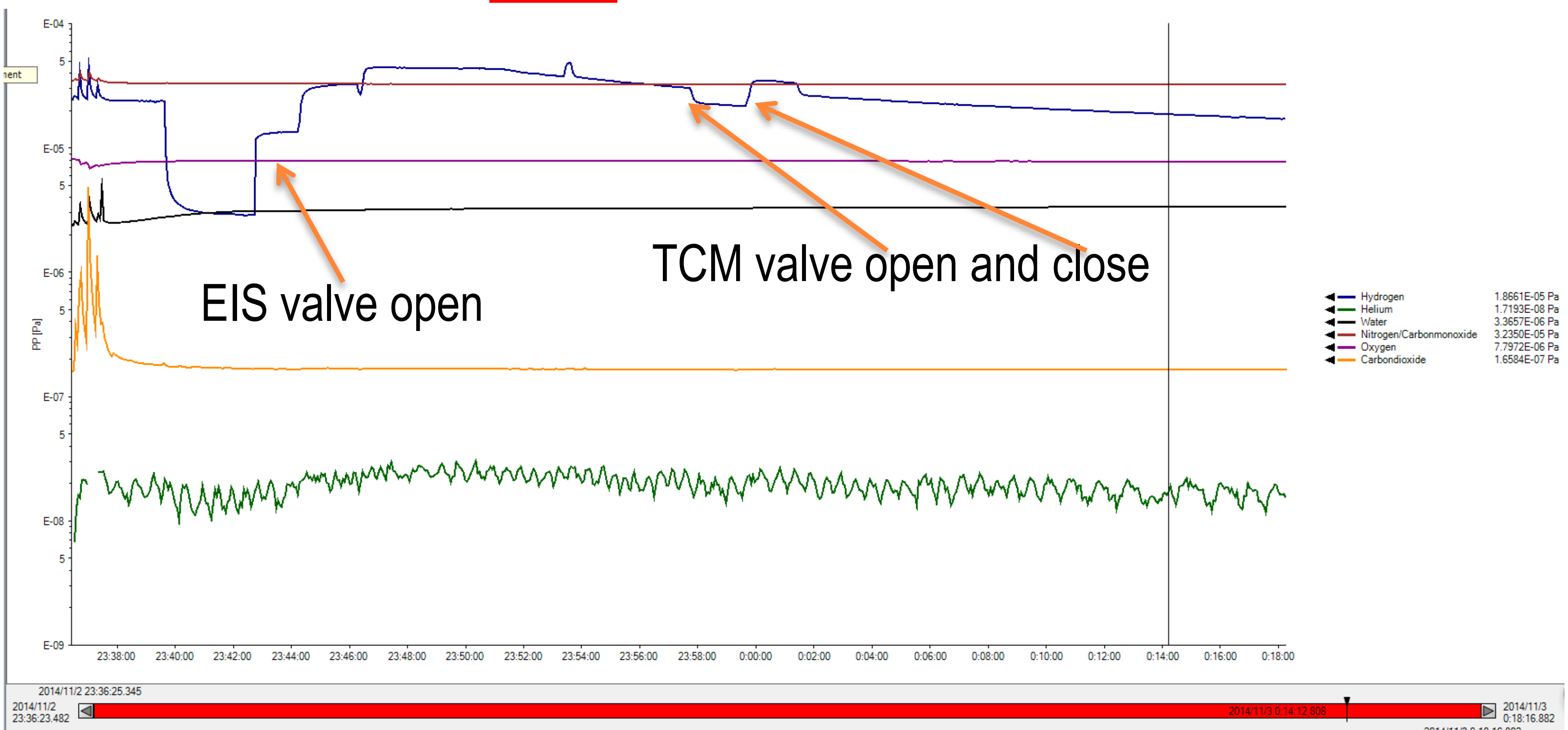


Fig.14. Increase of hydrogen pressure in the MEBT chamber during beam operation

SARAF Phase I linac in 2012, L. Weisman

Transfer of hydrogen at C-ADS





Issues of dynamic vacuum at SARAF

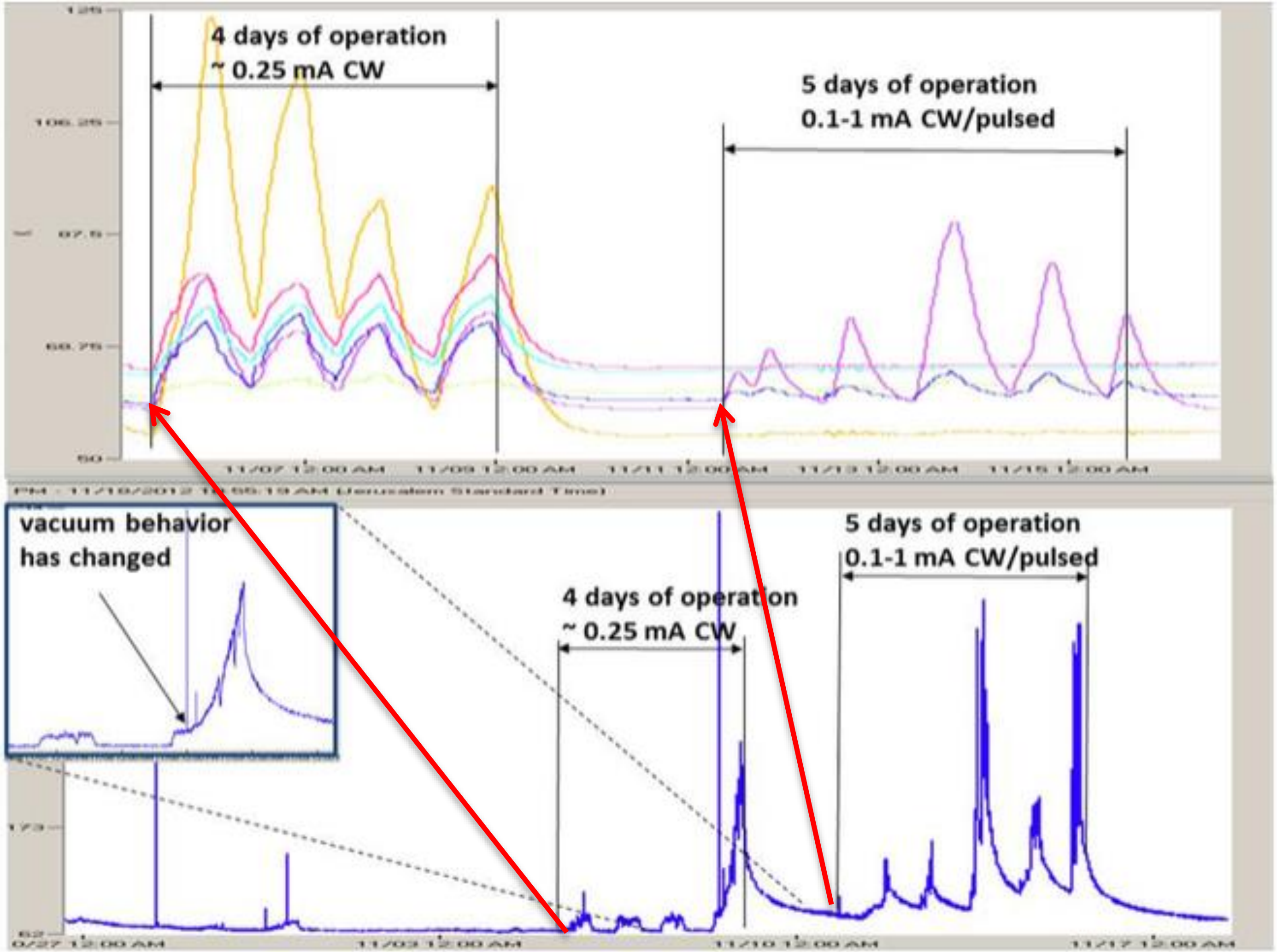
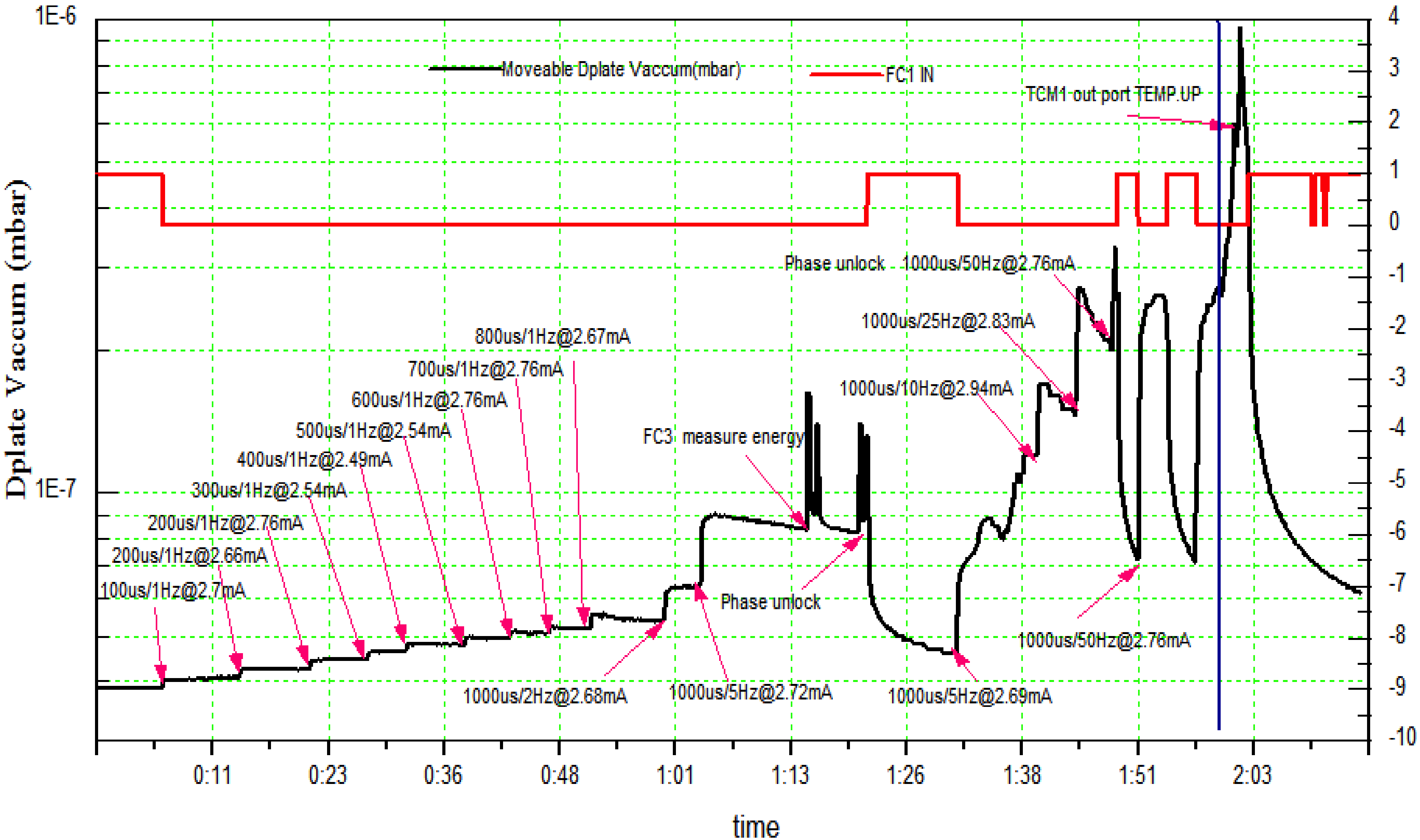


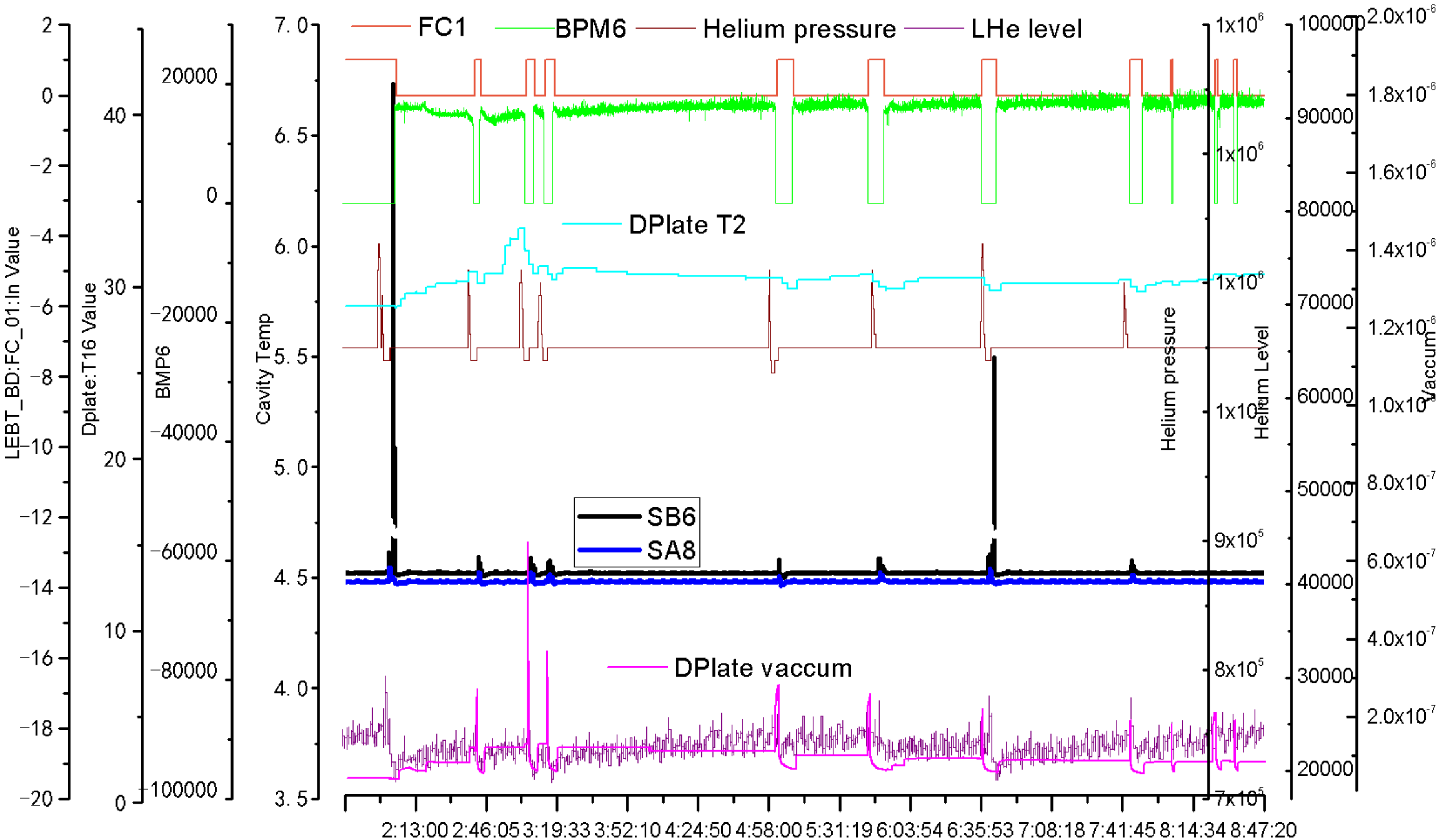
Fig. 22. The RF coupler temperatures (top) and the module vacuum pressure logs during nine days of continuous operation

SARAF Phase I linac in 2012, L. Weisman

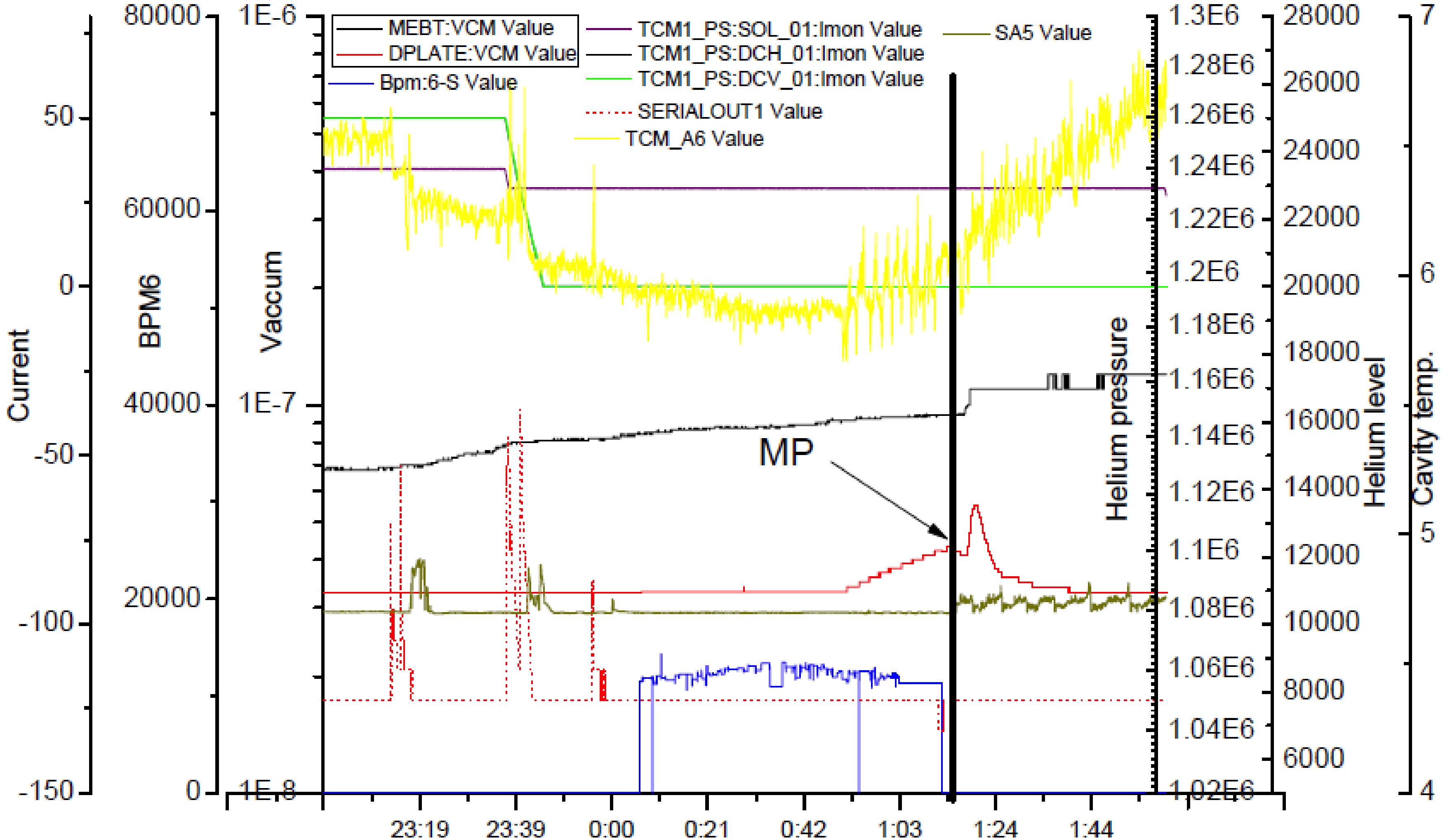
Dynamic vacuum with beam at C-ADS



Influence of helium press at C-ADS

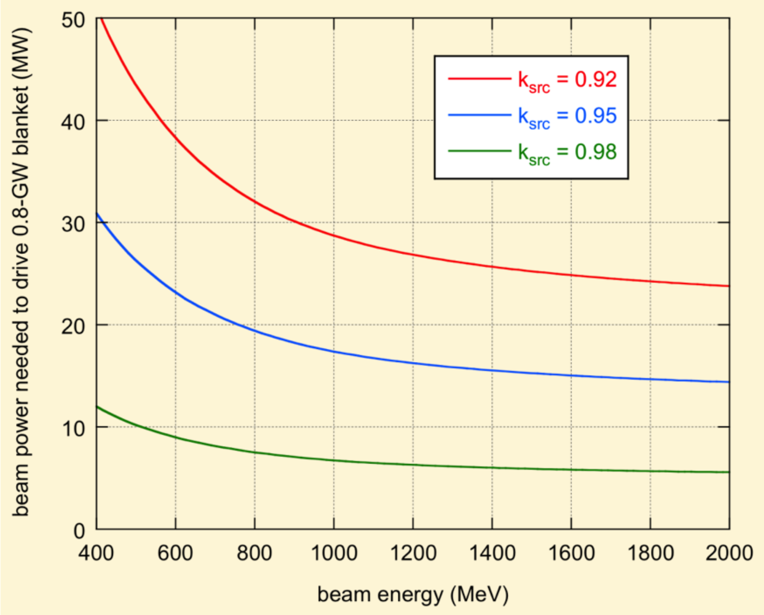


Superconducting Cavity DEAD! of C-ADS

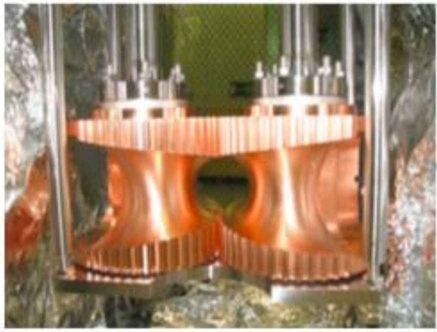


Whole TCM warm up to room temperature. Bake couple and sc-cavity to recover

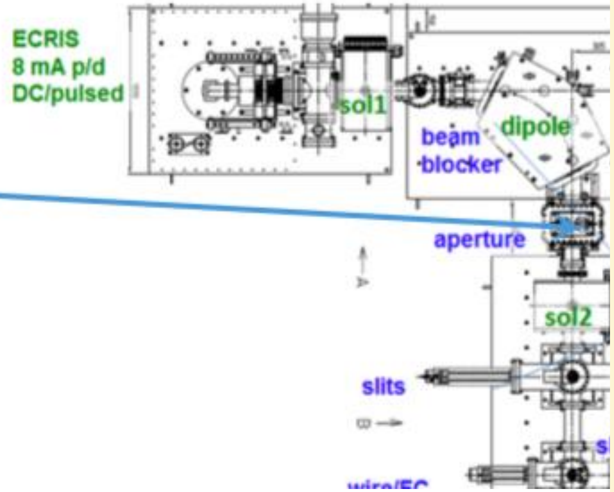
Current control with aperture at LEBT

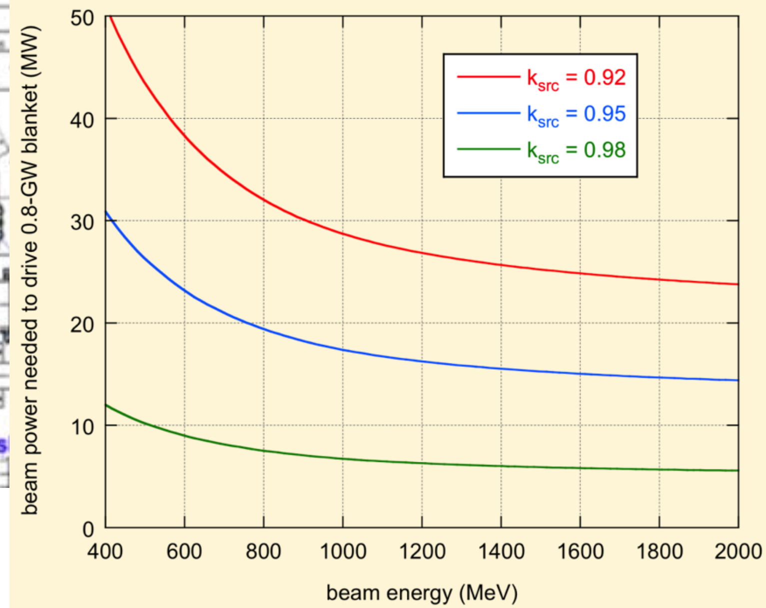


Current control with aperture at LEBT



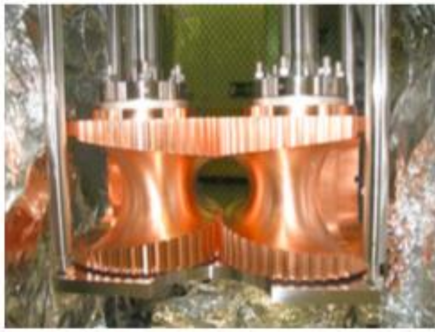
Varying the aperture together with Sol1 allows changing the beam intensity by almost factor 100.





SARAF Phase I linac in 2012, L. Weisman

Current control with aperture at LEBT



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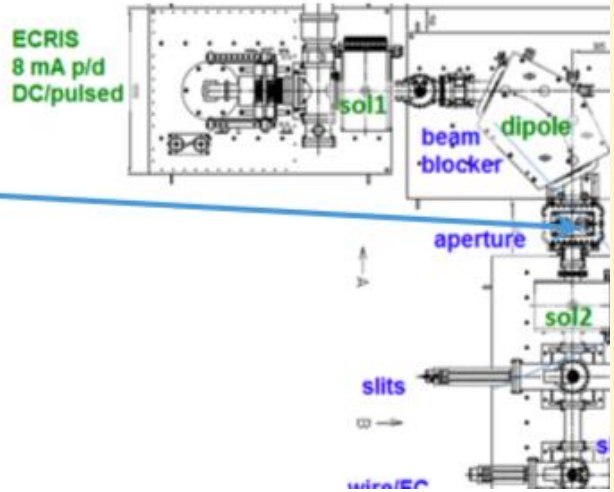
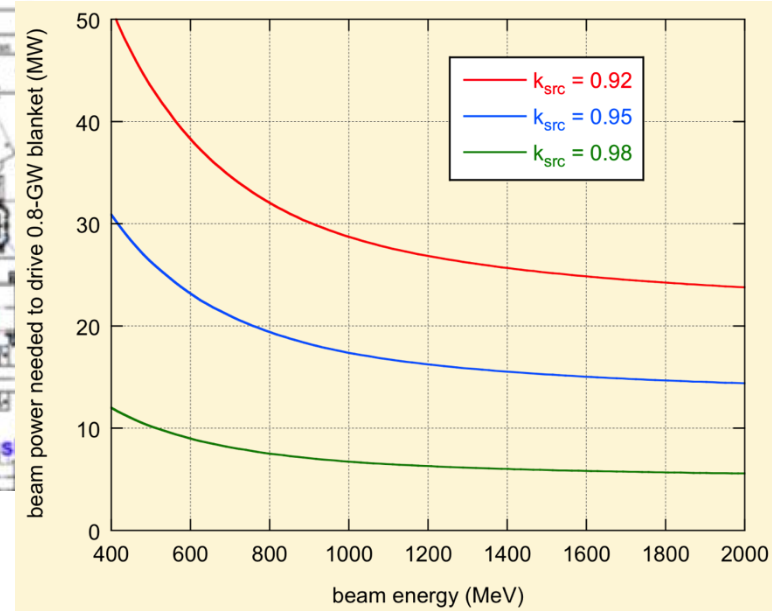
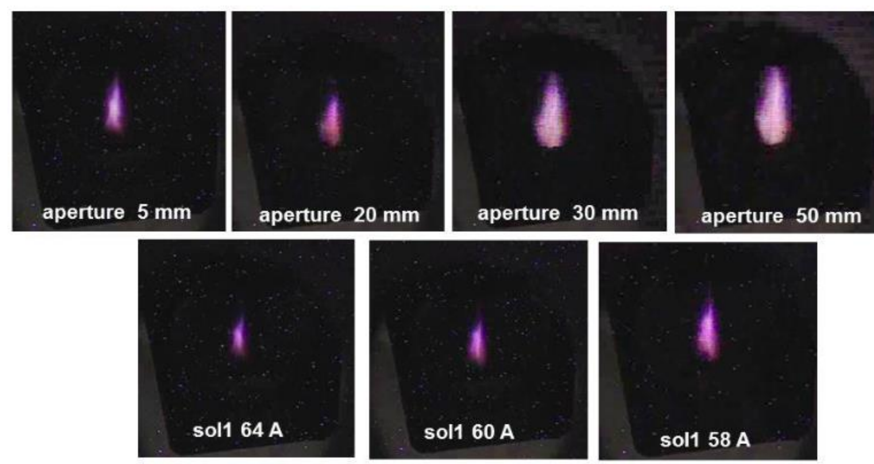
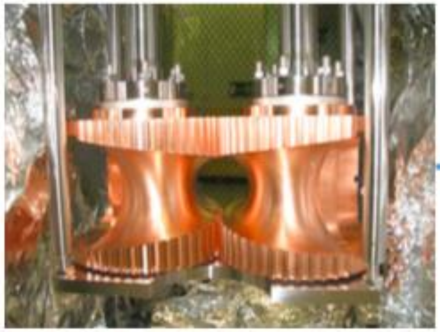






Current control with aperture at LEBT



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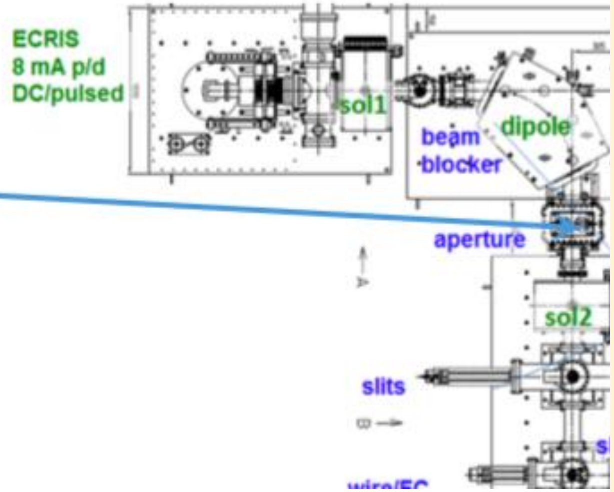
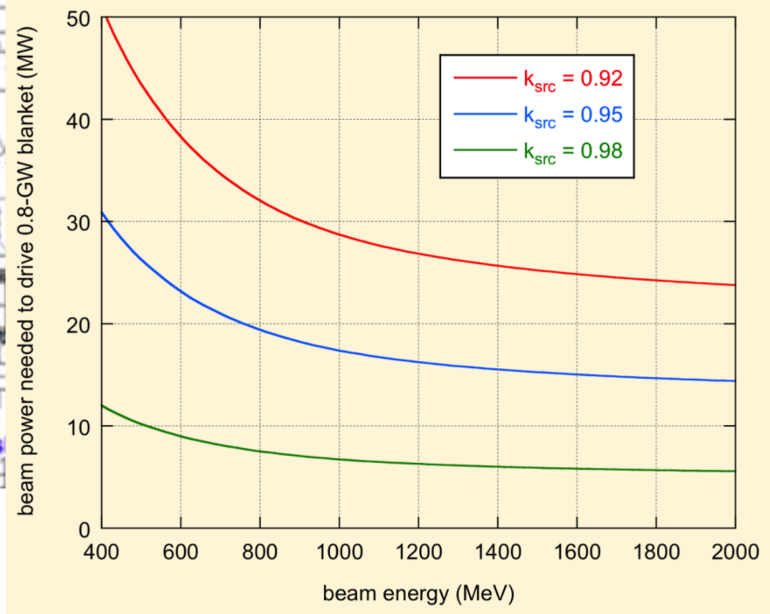




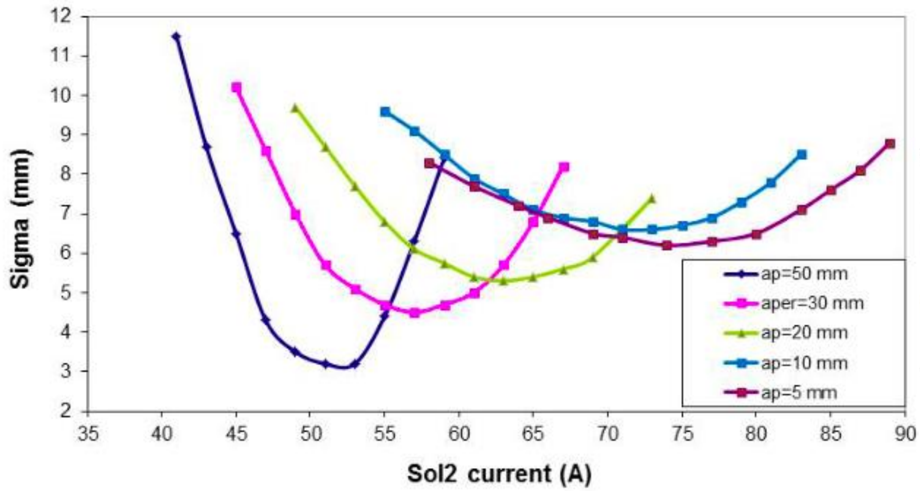
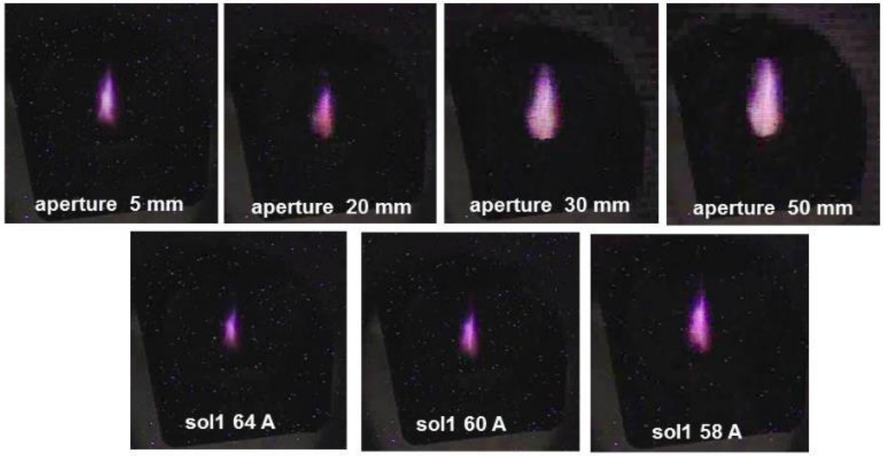
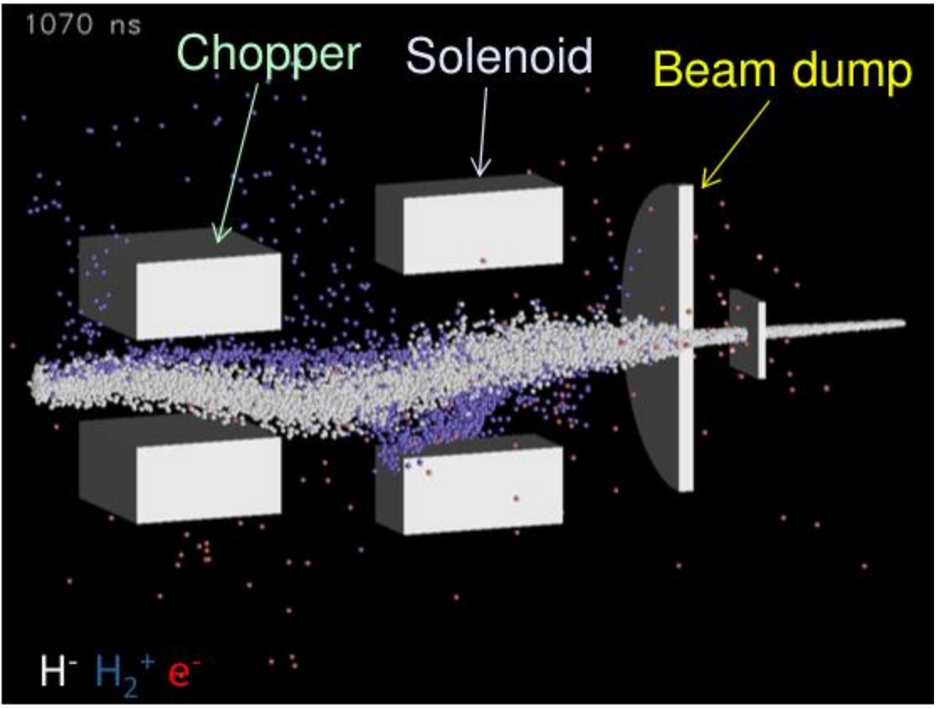


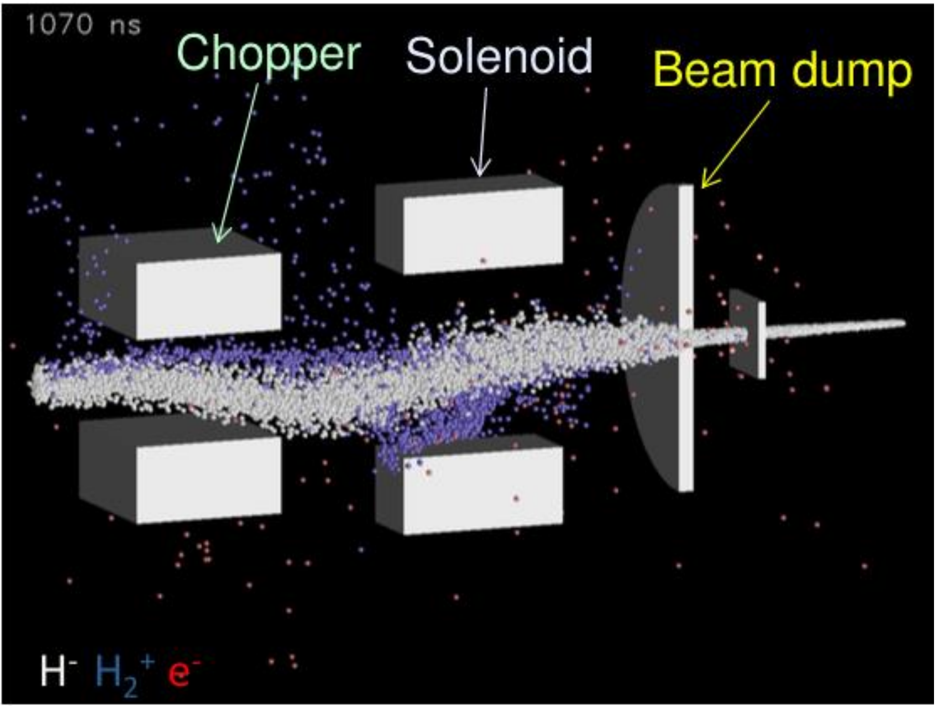
Fig. 6. The size of the beam as a function of the second solenoid current for aperture diameter values.



Duty factor control with chopper



Duty factor control with chopper

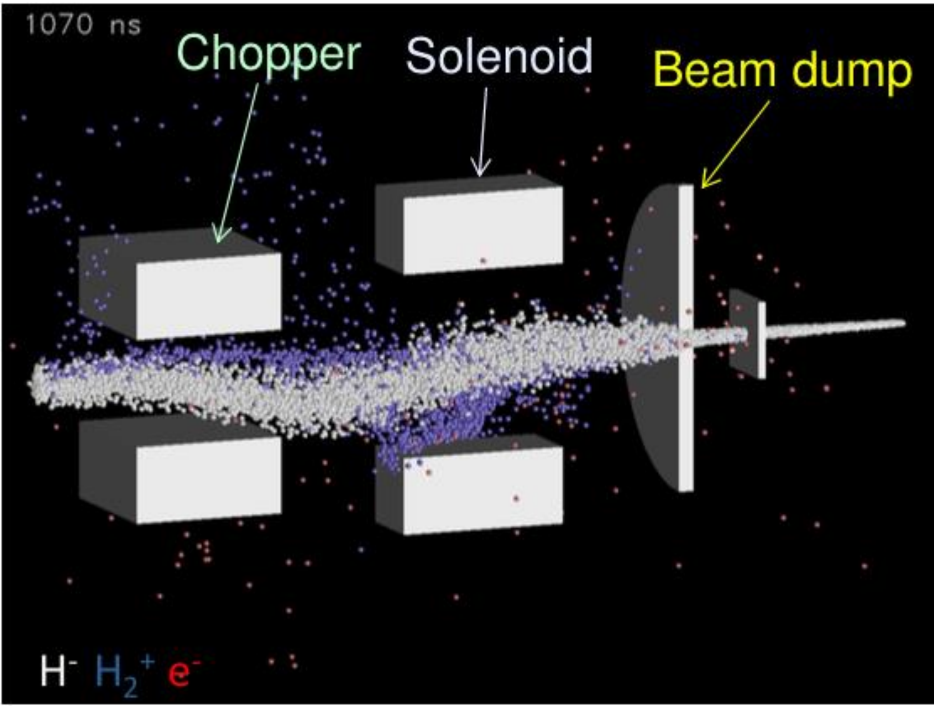


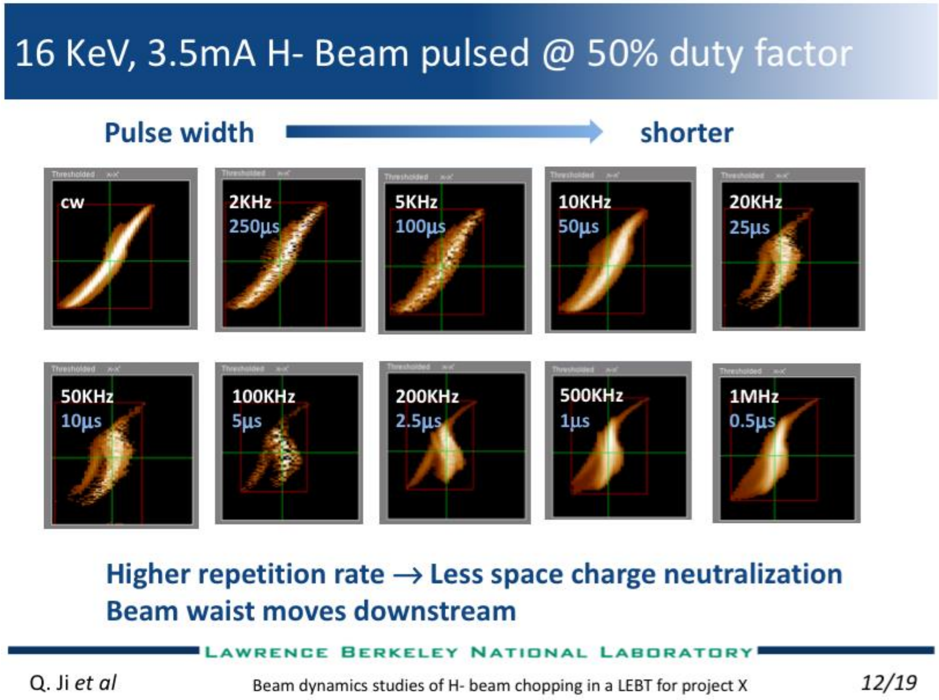
Time-dependent simulation of LEBT chopper using WARP 3D, simulation including particle interactions with background gas, such as: charge exchange, ionization, detachment.

Duty factor, pulse length and frequency all affect the quality and twiss parameters of the beam.

Operation mode transition from pulse mode to CW, beam will be out of control.

Duty factor control with chopper





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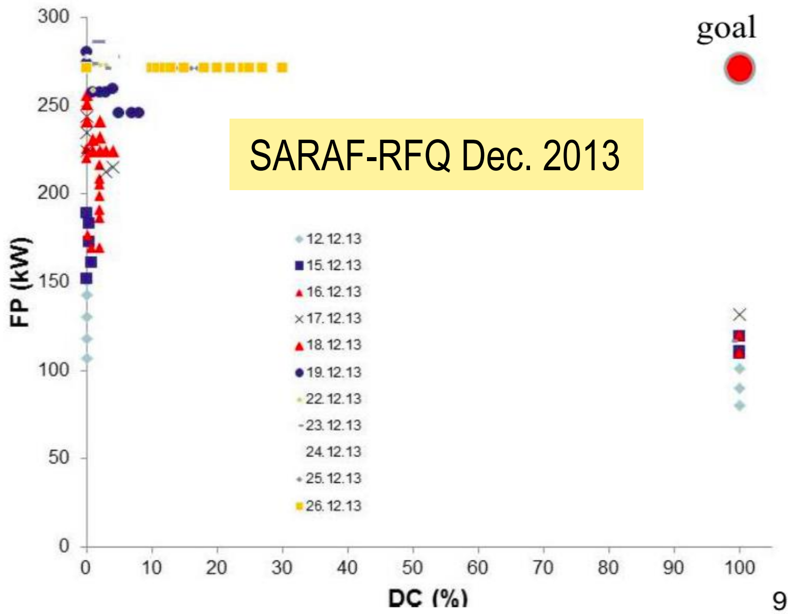
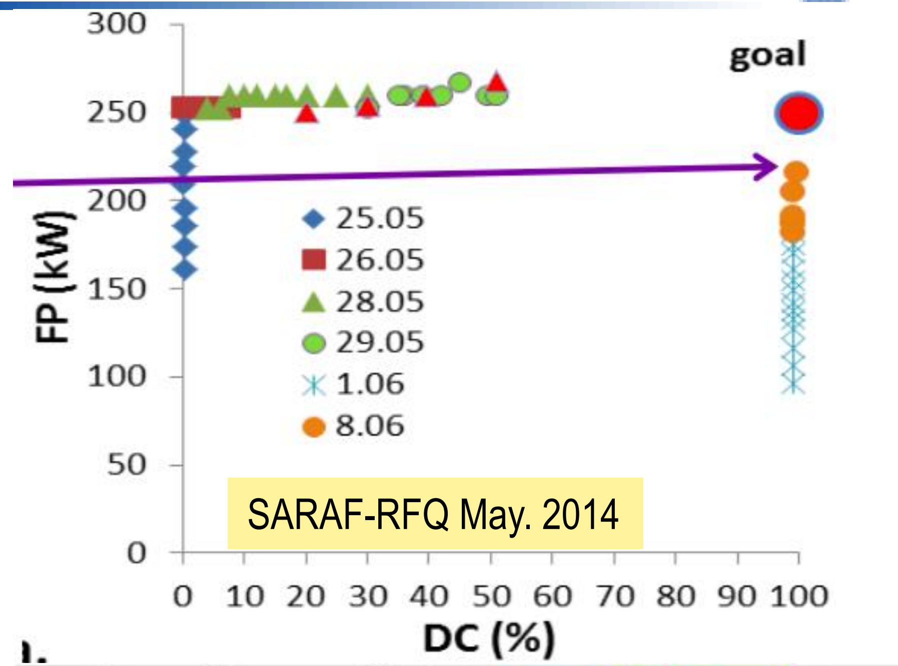
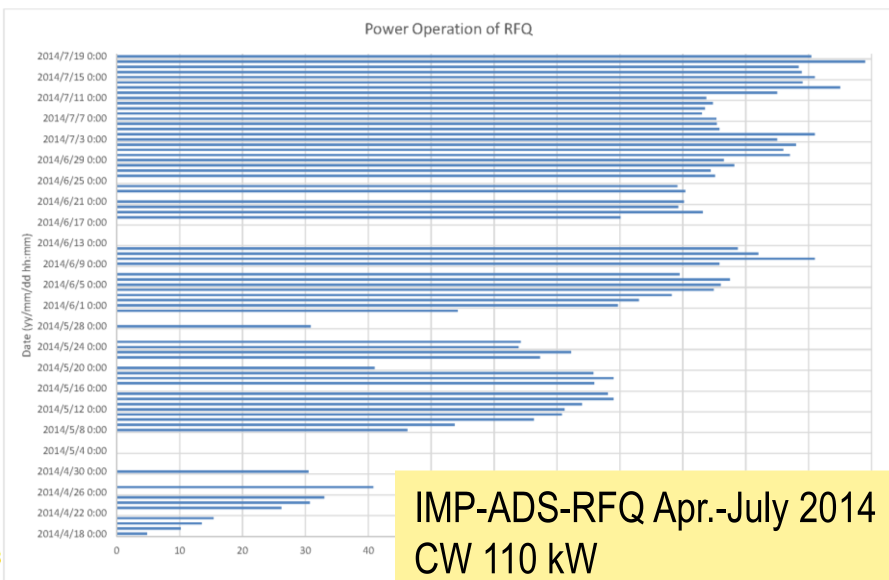
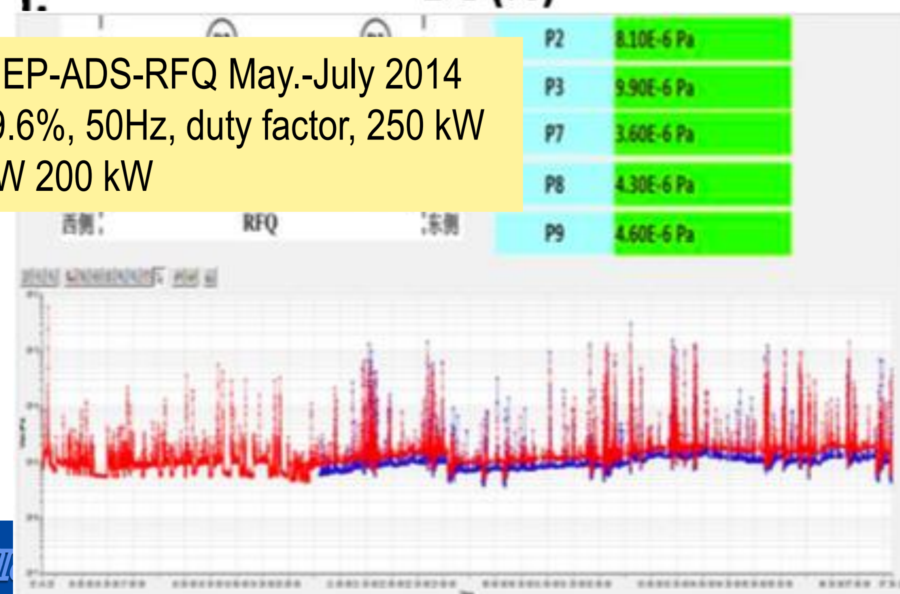
RFQs conditioning to CW

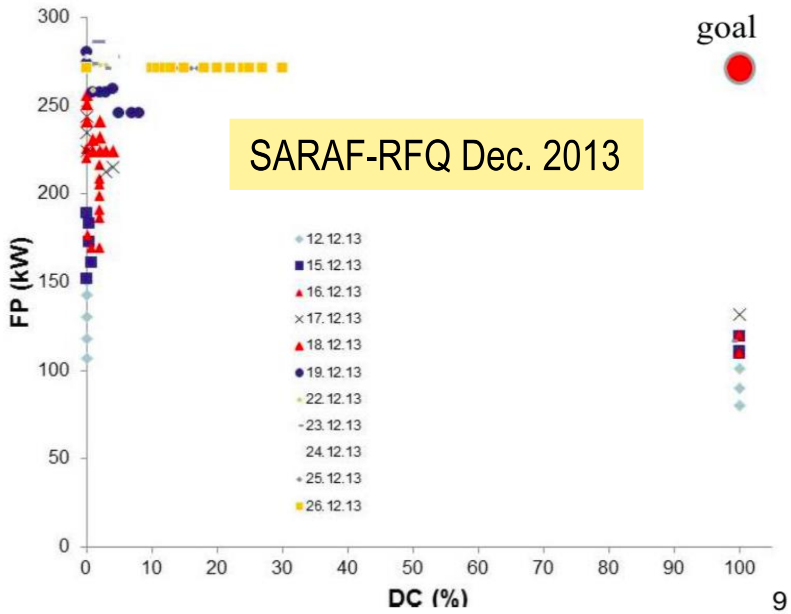




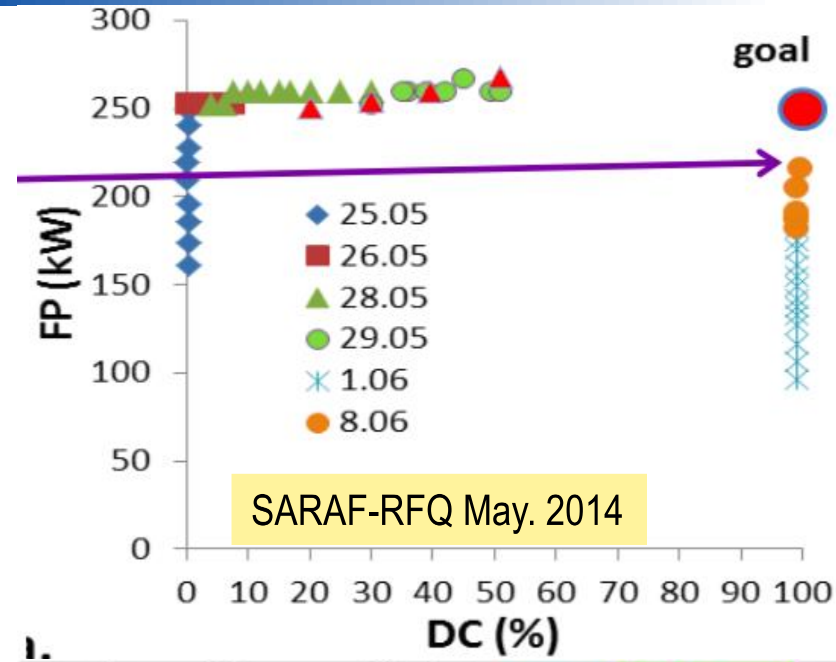




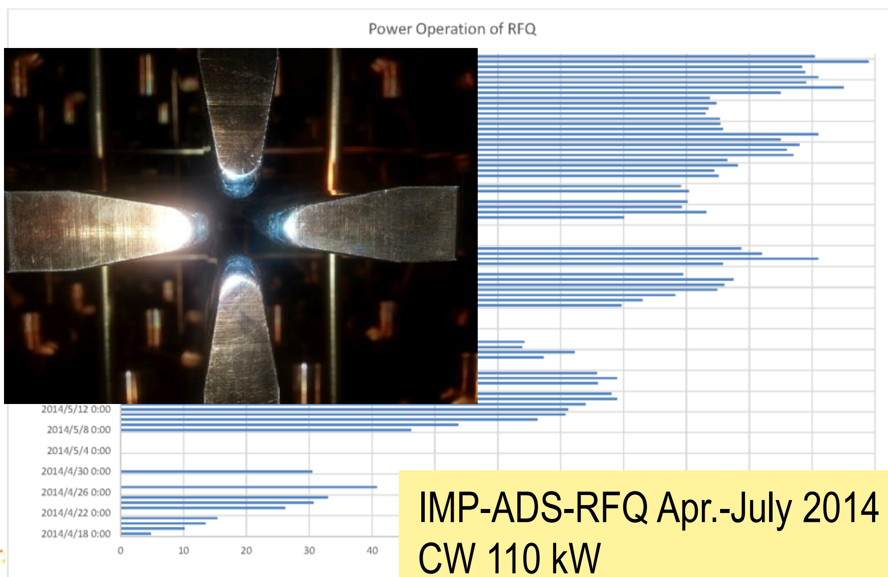
RFQs conditioning to CW



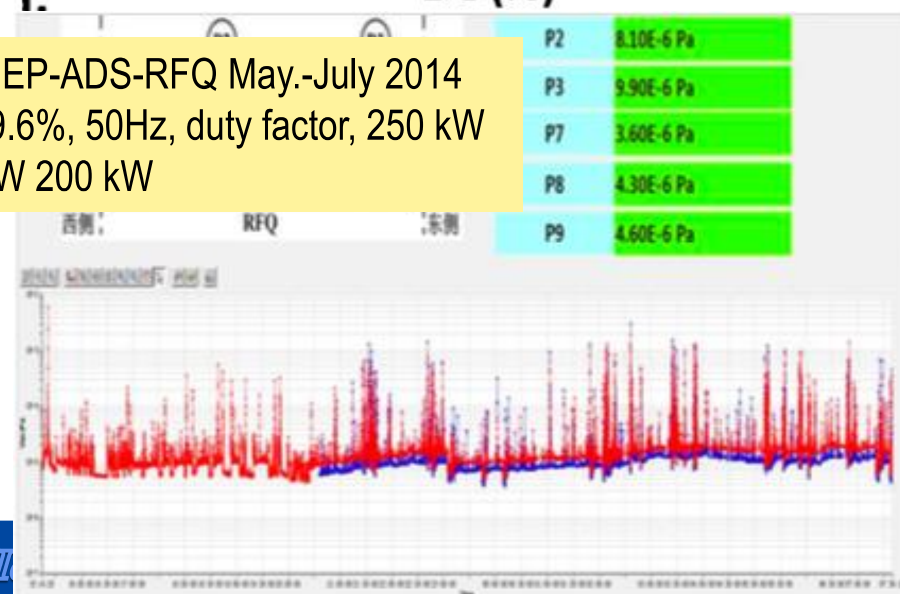
SARAF-RFQ Dec. 2013



SARAF-RFQ May. 2014



IMP-ADS-RFQ Apr.-July 2014
CW 110 kW

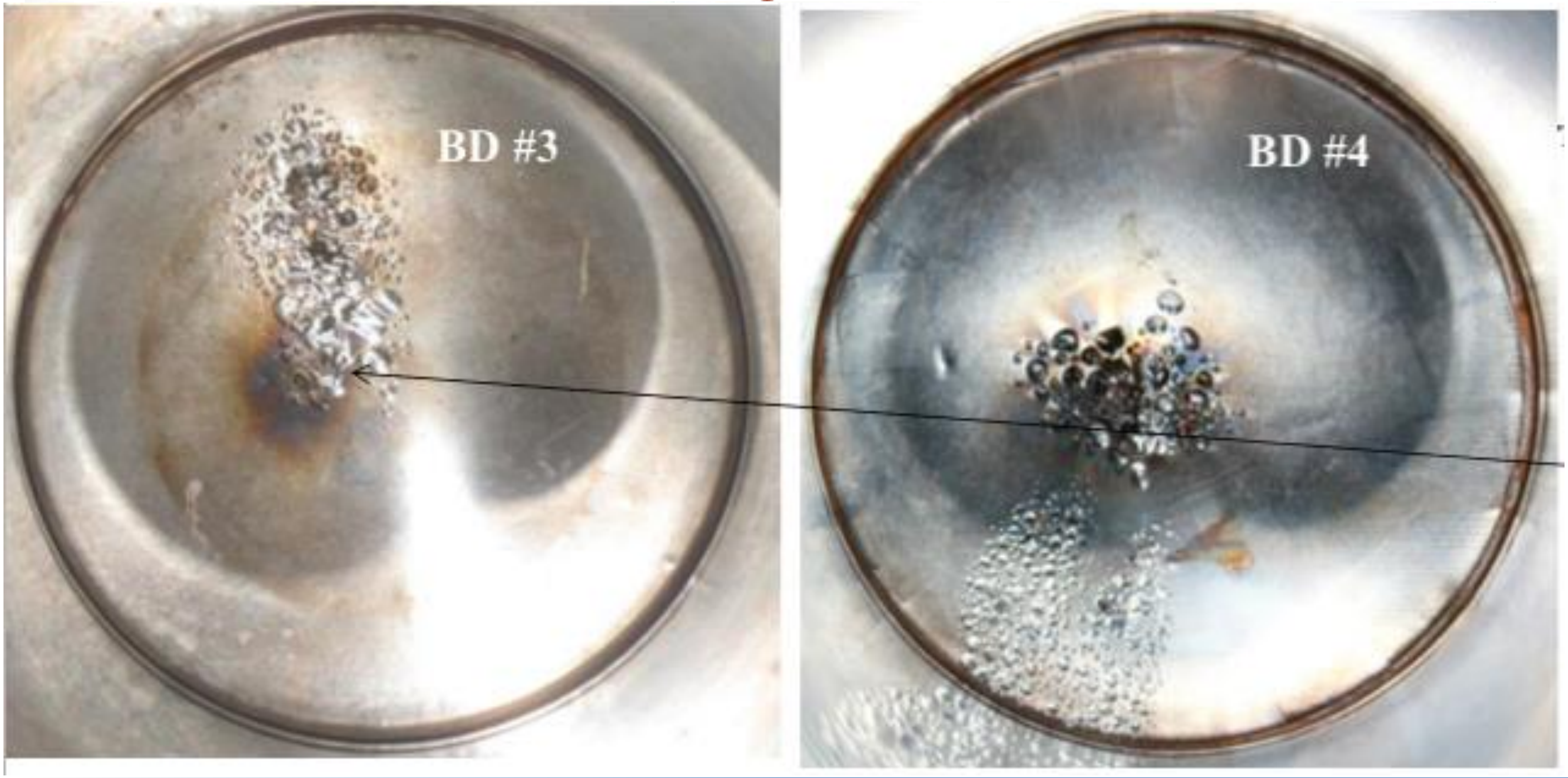


IHEP-ADS-RFQ May.-July 2014
99.6%, 50Hz, duty factor, 250 kW
CW 200 kW

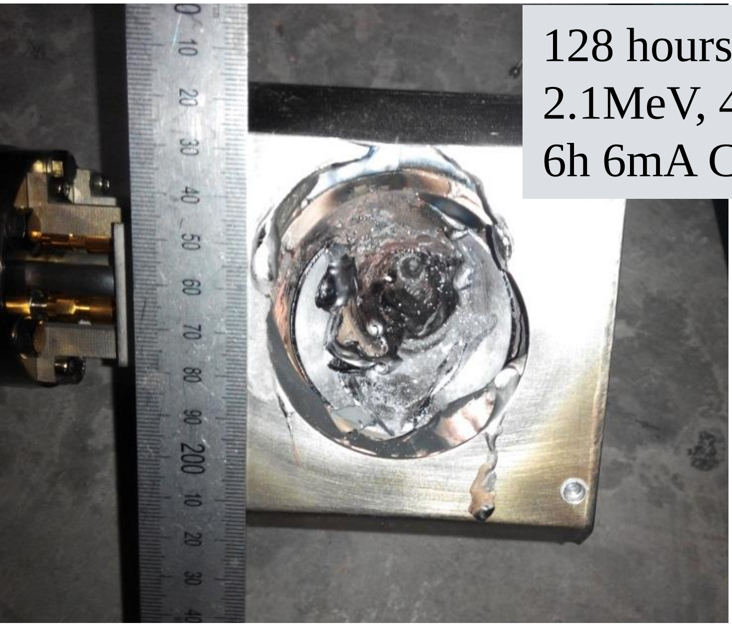
Damage of dual-metal dump of SARAF

Tungsten beam dump blistering problem

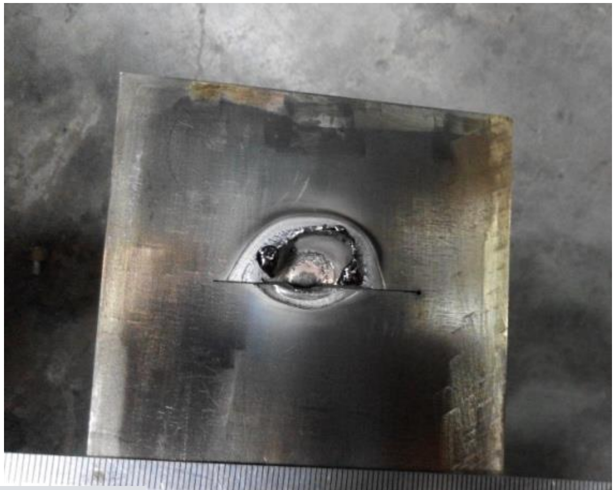
The 250 micron Tungsten sheet fused to a water cooled cooper plate beam dump exhibits remarkably low prompt and residual radiation at phase I beam energies. However, it suffers from severe blistering effects. (Generation 2 and 3).



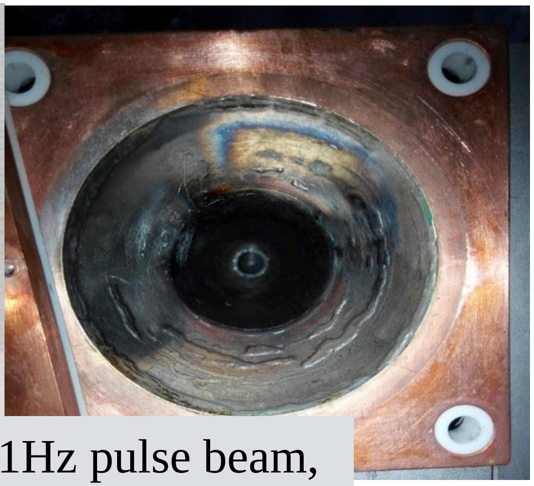
Damage of Tantalum Faraday Cup and Slits of injector II of C-ADS



128 hours beam including 2.1MeV, 4.5h,10mA, and 6h 6mA CW beam.



2.1MeV, 6 h , 4mA, 1ms/50 Hz pulsed beam



2.46mA, 100ms/1Hz pulse beam, **Duty cycle**
10% 8h13m + 15% 1h27m

After Tantalum removed, Only copper basis sustained 2.1MeV, 3.5h,10mA, CW beam without damage.

Summary

- To an accelerator for ADS, the challenges in physics and especially in technology are just touched when we design and commission the machine.
- The things are listed in the talk just a little. Understanding will be strengthened or change while we play with the demo machine.
- The plan of tuning of 5-MeV/10-mA is in 2015, some of the challenges will be overcome and some new will come out in the near future.

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Acknowledgements

Thanks for your attention

&

Team of China ADS Linac

Thanks for the help

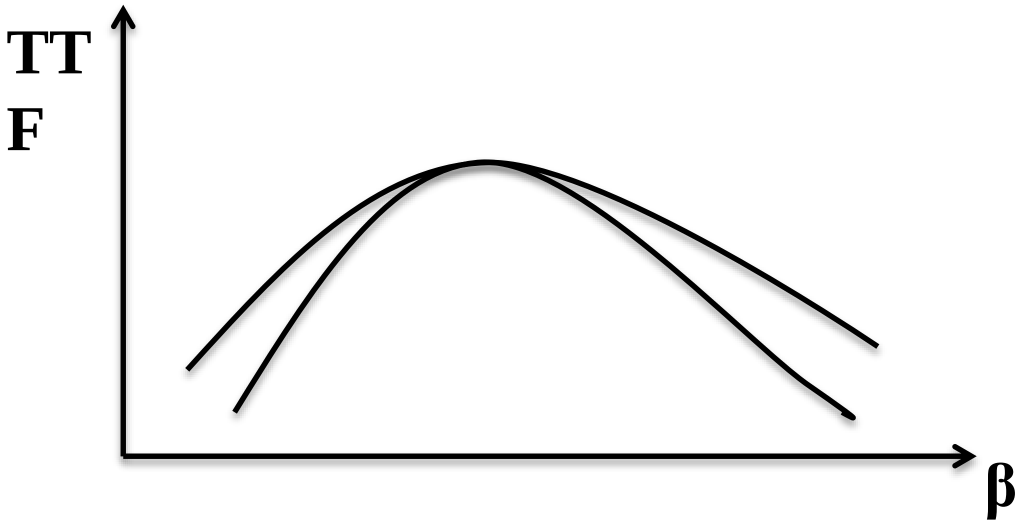
From LBNL, ANL, JLab, MSU/FRIB, FNAL, ORNL, TRIUMF, CEA/Saclay, IPN/Orsay, Frankfurt Univ./IAP, RIKEN, KEK, ……

HIT, PKU, SINAP,……

All of our progress would be impossible without you!

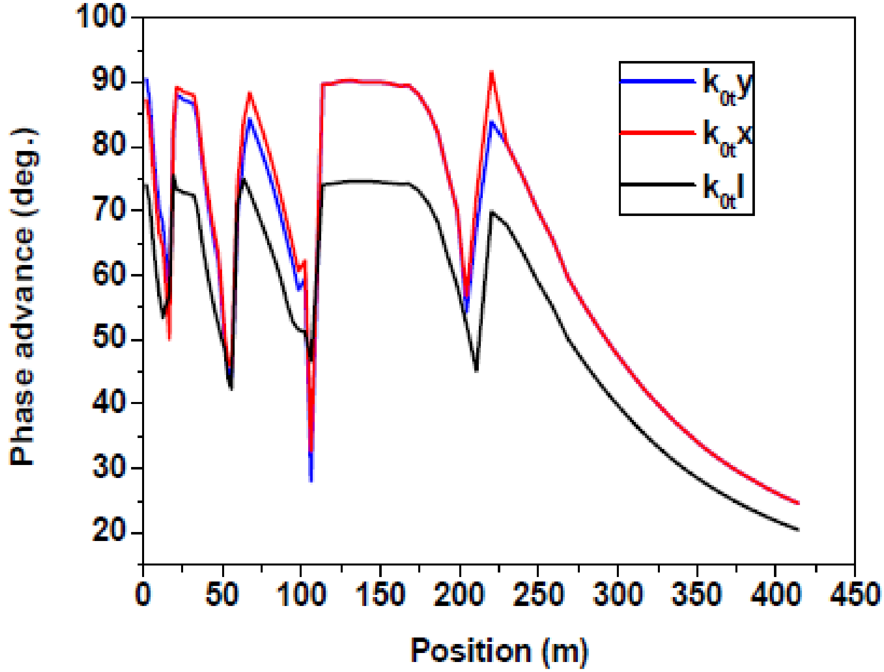
Cavity family choice - Normalized TTF

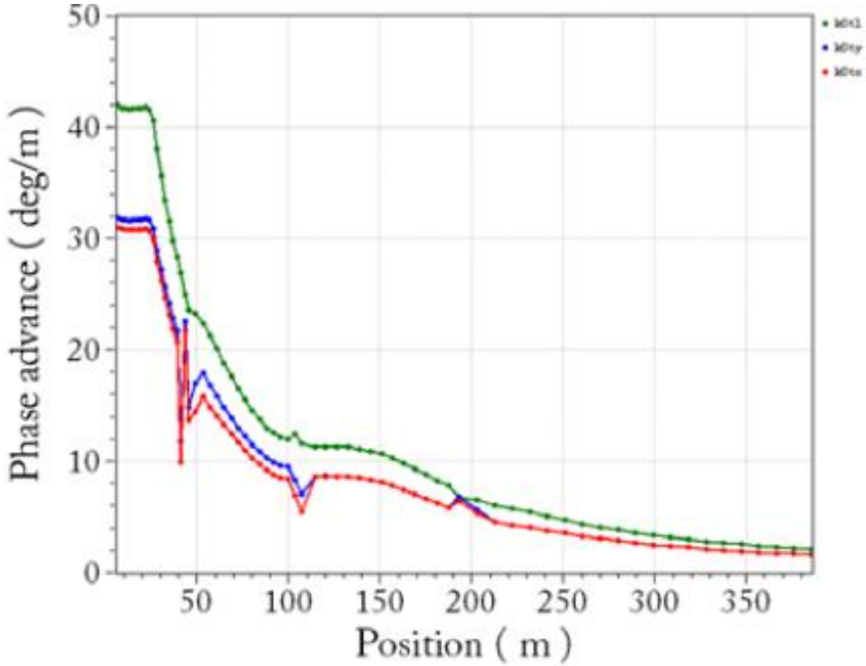
- The optima beta value
- The input and output energy of each beta section
- The optimized acceleration efficiency



$$\sum_{i=1}^{l}\frac{TTF_i}{l*TTF_{\mathrm{opt}}}+\sum_{i=1}^{m}\frac{TTF_i}{m*TTF_{\mathrm{opt}}}+\cdots+\sum_{i=1}^{n}\frac{TTF_i}{n*TTF_{\mathrm{opt}}}$$

Periodic structure design optimization





- The initial and final period phase advance of each section
- To keep the "K" value smooth（K=σ/L）

$$\frac{\text{Phase advance}}{L_1} = \frac{\text{Phase advance}}{L_2}$$

Roadmap of ADS Project in China

Goal in 2014, 5 MeV

Goal in 2015, 10 MeV

Stage 1: Research facility

(~10 MWt, ~2022)

key technology R&D

Stage 2: Exp. facility

(~100 MW$_t$, ~2032)

Stage 3: Demo facility

(~1000 MW$_t$, ~2040)

"strategic Priority Research Program" of the Chinese Academy of Sciences